FINAL/SCIENTIFIC TECHNICAL REPORT

DOE Award # DE-FC36-04GO14261

Chattanooga Fuel Cell Demonstration Project

Period of Performance

Start Date: July 2004
Projected End Date: March 2006

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Objectives

The overall objective of the Chattanooga fuel cell demonstration project was to:

- Develop and demonstrate a prototype 5-kW grid parallel, solid oxide fuel cell (SOFC) system that coproduces hydrogen, based on Ion America's (IA's) technology
- Transport, install, and commission the SOFC system in the Alternative Energy Lab located at the University of Tennessee at Chattanooga (UT-Chattanooga)
- Demonstrate efficiency and reliability of the unit in operation using natural gas (NG)
- Explore strategies to enhance efficiency and reliability of the unit

Technical Barriers

This project addressed the following technical barriers from the Technology Validation section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- C. Hydrogen Refueling Infrastructure.
- F. Centralized Hydrogen Production from Fossil Resources.
- I. Hydrogen and Electricity Coproduction.

Contribution to Achievement of DOE Technology Validation Milestones

This project contributed to the achievement of the following DOE technology validation milestones from the Technology Validation section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- *Milestone 11: Validate cost of producing hydrogen in quantity of $3.00/gge untaxed.* Technology validation of the IA 5-kW class SOFC system that coproduces hydrogen and electricity is a critical step towards validating the cost of producing hydrogen in quantity of $3.00/gge untaxed using solid oxide systems produced in high volume.[1,2]
- *Milestone 12: Five stations and two maintenance facilities constructed with advanced sensor systems and operating procedures.*
  Successful operation of the IA SOFC by the faculty and the graduate students provided an invaluable learning experience upon which to build operating procedures and sensor systems for safety under practical usage. With a successful demonstration of the fuel cell, consideration was given to construction of both prototype fueling stations and maintenance facilities.
- *Milestone 13: Total of eight stations and four maintenance facilities constructed with advanced sensor systems and operating procedures.*
  Continued successful operation of the Alternative Energy Laboratory together with successful experience with the prior stations and maintenance facilities will lead to an expansion and improvements in the installed base of stations and maintenance facilities.
- *Milestone 14: Validate $2.50/gge hydrogen cost.*

Cost reduction of critical components and development of larger SOFC systems at IA in high volume should enable future systems to achieve hydrogen costs below $2.50/gge.

Accomplishments

- 1st completely autonomous planar SOFC system monitored remotely from Sunnyvale, CA
- 1st known completely autonomous "state machine" mode operation of SOFC system
- 1st known demonstration of planar SOFC fuel cell system for hydrogen and electricity coproduction
- 1st planar SOFC system to successfully demonstrate hydrogen recycle
- Demonstrated up to 5.1 kW of grid-tie power and hydrogen coproduction using Pressure Swing Adsorption (PSA) purification of the anode exhaust stream
- Achieved hydrogen purity with <10 ppm CO (lower detectability limit of online gas analyzer)
- Achieved hydrogen purification yields of up to 90%
- Demonstrated controls strategy for operating PSA with 5-kW SOFC system
- System handled grid failure during operation in Sunnyvale
- Achieved peak system efficiency of 60.2% and peak DC stack efficiency of 37.7%
- Inaugurated the UT-Chattanooga Alternative Energy Lab

Introduction

The hydrogen economy will be enabled by creating a dense network of systems that are able to generate, store, and dispense cost-effective hydrogen on demand. Such a network will enable the proliferation of equipment (such as PEM fuel cell cars) requiring cost-effective hydrogen for their operation. Manufacturing and deploying these early systems carries significant economic risk, since they will generally be used with low capacity factor, until an adequate supply of end users demands the hydrogen on a regular basis. Low capacity factor translates into higher capital cost per unit of delivered hydrogen and presents a barrier to companies manufacturing these early devices. Systems capable of providing other valuable benefits during times when demand for hydrogen is low enable high capacity factors for systems deployed early in the build out of the hydrogen generation network, thereby nurturing the economic growth of the hydrogen economy.

IA developed a prototype SOFC system that is capable of efficiently generating electricity while coproducing hydrogen. SOFCs generate electricity at elevated temperatures where reforming reactions occur rapidly. When fuel (such as NG) is fed into the cell, the fuel is reformed (to mostly carbon monoxide and hydrogen). Part of the reformate is oxidized (for electricity generation), and part of it is purified as a hydrogen product. The amounts of electricity and hydrogen produced can be controlled automatically or by an operator (manually dialed in) across a range of utilization space. SOFC technology has been identified by DoE as potential attractive solution and is mentioned in its Fuel Cell Report to Congress (pp 4). The DoE has included work on this technology in its R&D partnership program. The Enterprise Center (Chattanooga, TN) facilitated a valuable and synergistic collaboration between a start-up business – IA (Sunnyvale, CA), the government (the City of Chattanooga and the DoE), and an academic institution – UT-Chattanooga to work cooperatively in order to expedite the field demonstration of IA's early prototype.

The technology is easily scalable from enterprise applications and filling stations to residential size, operates on most hydrocarbon fuels (e.g., NG, coal gas, ethanol), and produces low CO_2 emissions due to its high efficiency. The Chattanooga Fuel Cell Demonstration Project reported herein is an initial and independent evaluation of a practical fuel cell based on the unique SOFC technology developed by IA.

Approach

As a part of this project, IA was to construct and prepare a working prototype of a 5-kW class SOFC fuel cell based on their proprietary technology. The working prototype was to be constructed to the point where it would be ready for testing at a test facility located in UT-Chattanooga. The system required scaling from the 1-kW class, previously tested at Ion America laboratory, up to a 5-kW class unit with the necessary balance of plant (BoP) equipment to enable operation and coproduction of up to 5 kg H_2/day (5 GGE/day), which is enough to completely refill a fuel cell car on a daily basis. This project was to demonstrate a practical application typical of the environment in which the system co-produces electricity and or hydrogen. The unit was to be packaged, shipped, and installed at the UT-Chattanooga's Alternative Energy Lab. In Chattanooga, the prototype was to be placed in a test facility and subjected to a regimen of testing to prove it has the potential to be utilized to power strategic location or deliver hydrogen capable of serving as automobile fuel. A subset of the evaluation was to examine the design and measure in detail its performance to identify and recommend changes that can improve the production efficiency and cost metrics of electrical power or hydrogen.

Results

The UT-Chattanooga designated a building on campus for the purpose of creating a fuel cell testing laboratory. The building is located adjacent to the UT-Chattanooga SimCenter on the southeast corner of the campus. Under the present cooperative grant the laboratory was designed, constructed, and commissioned as the Alternative Energy Lab for testing the IA SOFC system with coproduction of hydrogen.

IA established detailed design requirements for the SOFC system based on the City of Chattanooga and the DoE contract requirements. Design requirements include system safety requirements, electrical interface requirements to the utility grid, chemical feed stream and exhaust requirements, mechanical, installation, and interface requirements from the SOFC operating site, and operating and performance requirements. From the system requirements, the system architecture was established. The system architecture was validated using ASPEN Plus modeling. Chemical, thermal, and electrical designs were captured in a piping and instrumentation diagram, wiring diagram, and communication interface. A power budget was estimated, and system performance projections were prepared. The system design was frozen in order to begin subsystem design.

Chemical compositions and thermal parameters were calculated at critical locations in the system, and a control sequence was developed using a “state machine” (automated system operation following a predefined path of steps, whereby each step has a set of conditions for completion after which it moves to the next step, to ultimately end up in steady state operation). Both stack and BoP designs were frozen in order to support parts procurement.

A detailed Bill of Materials (BoM) was specified. Special vendor requirements were being captured in the form of Computer Aided Design (CAD) package of drawings. Component and subsystem test equipment were set up and system control software was written, tested, and debugged. All required component and subassembly tests for Quality Control (QC) and performance verification were completed and system assembly was completed. Subsystem requirements were defined. SOFC stack and BoP subsystem designs were completed. A Failure Modes Effects Analysis (FMEA) and safety analysis of the system was performed. Subsystem designs were frozen. Components and subsystem designs were qualified. An end-to-end system test of the hot box (including SOFC stacks), warm box, and LabView control system was performed using a 5-kW class SOFC system platform developed by IA. The test validated the hot box and warm box designs. Data from the test was collected, and was used to make several improvements to system components and to control algorithms that are used in the state machine. The revised state machine was updated and ported to a PC-based control platform.

Hydrogen purification subsystem testing was performed using a PSA with an Online Gas Analyzer (OGA) to test purity of the product hydrogen. A Gas Chromatograph (GC) was used to cross check results of the OGA. Testing of the PCS system was performed, and an acceptance test was completed.

The project timelines are summarized in Figure 1. After successful completion of the System Test Task at IA (Sunnyvale, CA), the unit was packaged into multiple crates and delivered to UT-Chattanooga Alternative Energy Laboratory (Figure 2) on January 17, 2006. When the crates were delivered at the Alternative Energy Laboratory, various facility upgrade projects were still underway. The system was uncrated and assembled by January 21, 2006, while the infrastructure work related to electrical grid tie, water plumbing, exhaust duct work, network connectivity and natural gas connection was allowed to finish.

Upon receiving necessary approvals from Tennessee Valley Authority and State Fire Marshall’s office, the system was started on February 4, 2006, and by 4:00 PM on February 5, 2006 the system started delivering power to the grid (Figure 3). Congressman Zach Wamp, in the presence of various dignitaries, inaugurated the Fuel Cell at the Alternative Energy Laboratory on February 17, 2006 (Figure 3).

The results of the Chattanooga Fuel Cell Demonstration Project were presented, by Jim Henry (UT-Chattanooga) and Joe Ferguson (The Enterprise Center), at the 2006 Annual Merit Review Proceedings (May 16-19, 2006).

Jul 2004	**Proposed** project start date
Feb 2005	**Actual** signed contract and release of funds
Feb 2005	Requirements established and system specification defined
Aug 2005	Subsystem Design and Test tasks completed
Oct 2005	Stack and Balance of Plant (BOP) assembly tasks completed
Dec 2005	System logged 707 hours of operation on 19 Dec 2005 System completed 779 hours of operation at IA's Sunnyvale location before shipping to UT-Chattanooga
Jan 2006	System shipped to UT-Chattanooga on 13 Jan 2006
Feb 2006	System started 4 Feb 2006 at UT-Chattanooga System officially inaugurated by Congressman Zach Wamp on 17 Feb 2006
Jun 2006	System logged 3744* hours of operation and 11.32 MWh of AC power to the grid * Includes 779 hours and 2.05 MWh from Sunnyvale operation

Figure 1. Timelines for the Project

Hotbox getting ready for crating at Ion America

Loading fuel cell at Ion America

Trailer arriving at UT-Chattanooga Alternative Energy Lab

Unloading SOFC system at UT-Chattanooga

Figure 2. Shipping/Receiving/Installing SOFC System

Alternative Energy Lab at UT-Chattanooga with PSA H_2 purifier shown on the left

5-kW system installed and operational inside the Alternative Energy Lab on 5 Feb 2006

System inaugurated by Congressman Zach Wamp (right) on 17 Feb 2006

Figure 3. Fuel Cell Inauguration at UT-Chattanooga

DC efficiency:

$$\eta_{\text{stack}} = \frac{\text{DC power from stack}}{\text{LHV of fuel}}$$

Peak stack efficiency = 37.7%

System efficiency:

$$\eta_{\text{system}} = \frac{\text{total power (DC) + LHV of } H_2}{\text{LHV of fuel}}$$

Peak system efficiency = 60.2%

System parasitic losses:

→ BOP power at peak power as a % of total DC power = 10.7%

Figure 4. Key Metrics for Efficiency and Parasitic Losses

Response to Year 2005 Reviewers' comments

Listed below are selected reviewers comments (*in italic*), from the 2005 DOE presentation, and Ion America's response.

Does not seem likely that the large amount of work proposed (and needed) can be completed in next 4 months unless rate of progress on project is accelerated.

The project was completed without any additional funding from DOE.

While project is well funded for FY05, progress to date seems slow. Seems questionable whether system can be built, tested, and validated within remaining 4 months of project.

Project was successfully completed. Delays in early stages were attributed to contractual and funding hurdles to initiate the work.

This approach is very high risk and is not likely to achieve a 5 kW system as planned.

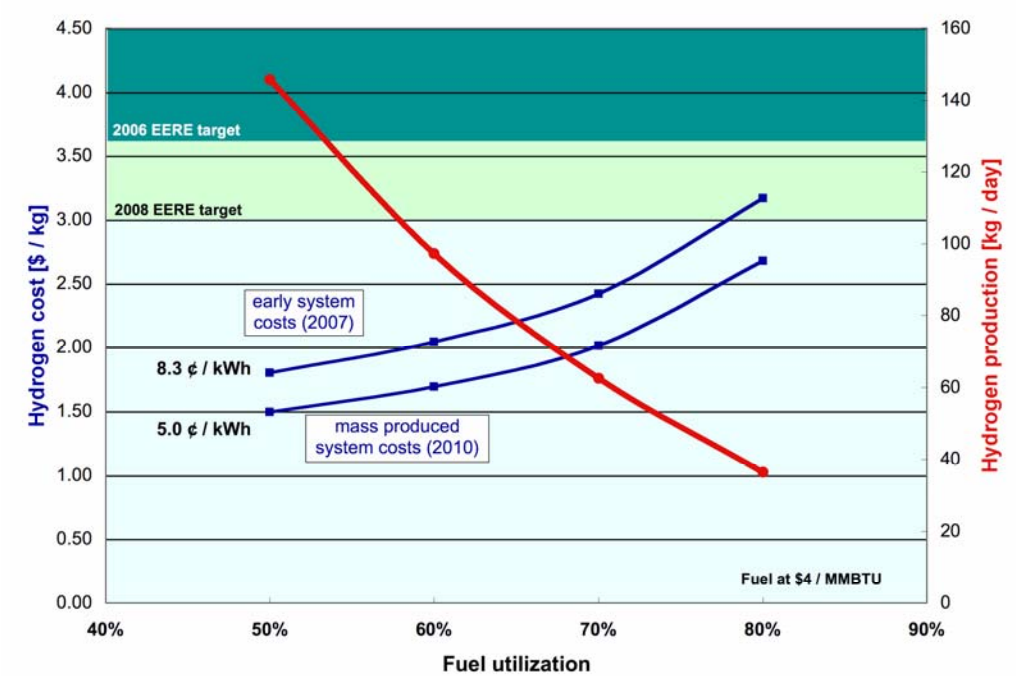
The overall project objective was successfully demonstrated.

There is no evidence of research to advance the technology, but rather a very expensive and risky build and test activity.

Chattanooga Fuel Cell project was the first known demonstration of SOFC for electricity and H2 cogeneration

It was also the first known completely autonomous "state machine" mode operation of SOFC system

This is an interesting project but it is not clear that it adequately addresses the hydrogen program cost goals.



Current domestic cost of hydrogen for mid-scale users (~100 kg/day) is approximately $10/kg.
EERE: U.S. Department of Energy's Energy Efficiency and Renewable Energy Program

Ion America's co-production units "will be" capable of producing electricity at competitive rates and also beat EERE's 2008 targets of hydrogen domestic cost.

The program does not emphasize direct hydrogen production but only considers hydrogen production as a by-product.

There is a very large and significant market, of great national relevance, where H2 as a co-generated product is very valuable.

Proving the approach with unproven solid oxide technology combines the risk of the approach with the risk of unnecessary fuel cell technology.

The Chattanooga Fuel Cell demonstration project successfully completed.

Approach may be flawed due to endothermic reforming of natural gas.

The fuel cell integration proves that the natural gas reformation can be efficiently accomplished from stack waste heat.

To produce extra hydrogen for vehicle applications high amounts of natural gas must be introduced into SOFC and the endothermic reaction will cool the cell.

Not true. Our quantitative modeling suggests otherwise and actual data from the Chattanooga system proves that our analysis is correct.

Performing demonstration/validation on a larger sized system (say 100 kW, rather than 5 kW) would provide more value to the program by removing questions of scale-up.

5kW size demonstrated in Chattanooga adequately covers the electricity needs of a typical home and produces enough hydrogen for daily complete refill of a fuel cell car.

The project does not deal with CO2 production issue.

CO2 is separated and concentrated in the PSA which can be sequestered.

Some interface to auto industry should be included. (Presenter mentioned a desire to provide home hydrogen auto fueling).

Interface to auto industry is beyond the scope of this project; it can be a follow on program if funds are available.

Industry / university collaboration. Interactions and collaborations with others seem limited.

Project success is attributed to successful collaboration between University of Tennessee at Chattanooga, The Enterprise Center, Ion America & its various industry partners.

The project should minimize CO2 release into atmosphere.

High efficiency of the system leads to less carbon dioxide production. Furthermore, high concentration of CO2 in the PSA exhaust can be easily sequestered.

3.1 System Definition

Ion America established detailed design requirements for the SOFC system based on The City of Chattanooga and The Department of Energy contract requirements. Design requirements included system safety requirements, electrical interface requirements to the utility grid, chemical feed stream and exhaust requirements, mechanical, installation, and interface requirements from the SOFC operating site, and operating and performance requirements.

From the system requirements, the system architecture was established. Chemical, thermal, and electrical, Process and Instrumentation Diagram, Wiring Diagram, Communication Interface, and Power Budget were updated, and system performance projections were prepared. The system and subsystem designs are being reviewed.

Task 3.1 Milestones

3.1.1. Start
3.1.2. Project requirements definition
3.1.3. System architecture design
3.1.4. P&ID, Wiring Diagram and Communication Interface
3.1.5. System performance projections
3.1.6. System design freeze

3.1.1. Start

The Chattanooga Fuel Cell Demonstration project started on July 1, 2004. Ion America signed a subcontract with UT-Chattanooga in November 2004, but commenced work in July 2004, in anticipation of the award. January 2005 was the first month with deliverables under the subcontract with UT-Chattanooga.

3.1.2. Project requirements definition

Siting

The exact location for installing the Fuel Cell system was specified by personnel at UT-Chattanooga with input from Ion America. The fuel cell was to be sited in “The Alternative Energy Laboratory” on MLK Blvd, Chattanooga, TN.

Safety

Ion America started working with Merlin CSI (San Diego, CA) for communication and control of the system. For all industrial safety related issues, Ion America worked with Environmental and Occupational Risk Management Inc. (Sunnyvale, CA). Ion America also retained the services of John Boyle & Associates (Emmaus, PA) as a consultant for hydrogen safety. Ion America also hired personnel who were experts in electrical safety.

Schedule

The initial plan was to deliver the 5 kW SOFC with hydrogen cogeneration by the end of September 2005. However, the project slipped until January 2006, because of the several important improvements were made to increase electrical output, increase efficiency, and prolong the operational life of the system, as elaborated on pages 33-34.

Specifications

Listed below are the initial specifications as defined by Ion America to comply with requirements as defined by The City of Chattanooga and The Department of Energy contract:

<u>Electrical:</u>
3-5kW AC out, 208V/3phase, 60 Hz, grid synchronized. The system was to be designed to comply with UL 1741, "Standard for Inverters, Converters, and Controllers for Use in Independent Power Systems".

<u>Interfaces:</u>
Input (Maximum):
Natural gas: 1.3 scfm at 10 psig (line pressure regulated to 10 psig)
Air to main unit: 35 scfm
Air to hydrogen purification unit: 12 scfm
Water: 5 gallons to start
Electricity: 208V/120V AC 60Hz (for startup)

<u>Output (Maximum):</u>
Stack Electrical DC: 6.5 kW
Net Electrical AC: 5.5 kW without PSA, 4.2 kW with PSA
Hydrogen: 5 kg/day
Water: 20 kg/day
Main exhaust: 30 scfm (N_2–80%, O_2–17%, H_2O–1%, CO_2–20 ppm)
PSA purge: 15 scfm (N_2–70%, O_2–15%, H_2O–6%, CO_2–9%)
Emergency vent: 2.5 scfm (H_2–58%, CO_2–36%, H_2O–4%, CO-1%)

<u>Hydrogen production:</u>
Up to 5 kg/day hydrogen out
Delivery pressure: up to 60 psig
Outlet pipe: 1/2 inch
Purity: >98% (projected for flow of 2-3 kg/day), online gas analyzer is available for CO_2, CO, and CH_4

<u>Inlet gas:</u>
Natural Gas
Maximum flow rate: 35 slpm
Nominal flow rate: 27 slpm

Minimum delivery pressure: 10 psig
Maximum delivery pressure: 15 psig (regulate to 10 psig)
Inlet pipe size: 1/2 in supply

Maintenance:
Sulfur filter replacement every 4,000 hours
Air filter cleaning or replacement nominally every 4,000 hours or more frequently in dusty environments
Inspect/replace diaphragms, valves, and seals in air pumps every 4,000 hours
Inspect/replace media in water purification system every 4,000 hours
Inspect/replace rings and valves in anode exhaust compressor every 4,000 hours

Environment and Operating temperature:
5C to 35C

Physical dimensions and weight:
The preliminary system dimensions and weight (excluding hydrogen purification unit) are given in Table 1. The dimensions and weight of the hydrogen purification system are also given in Table 2.

Description	Height (ft)	Length (ft)	Width (ft)	Weight (lb)
Hot Box	3	3.5	2	520
Warm Box	4.5	1.5	2	220
Electrical Box	1.5	3.5	3.5	380
Electronics Box	3	3.5	1.5	180
Water Purification	3.5	1.5	1.5	80
Frame and miscellaneous	-	-	-	450
System Excluding H_2 Purification	**4.5**	**5.5**	**3.5**	**1830**

Table 1. System dimensions and weight (excluding hydrogen purification).

Description	Height (ft)	Length (ft)	Width (ft)	Weight (lb)
Compressor with buffer tank	3	3.5	2.5	300
PSA	6	2	2	500
Exhaust Burner / miscellaneous	-	-	-	200
Total Hydrogen Purification System	**6**	**3.5**	**2.5**	**1000**

Table 2. Hydrogen purification system dimensions and weight.

3.1.3. System architecture design

The overall system architecture is shown in Figure 5. The system included 5 distinct components:

1. Hot box – This contained fuel cell stacks, reformer and high temperature heat exchangers. IA also identified a unique way of integrating a reformer directly into the hot zone in such a way that most of the stack heat could be directly used to supply the endothermic heat required for steam-methane reformation reactions.

2. Warm box – This component included all the fuel processing and humidification of natural gas. IA incorporated an innovative idea to use the air exhaust heat for humidification purposes.
3. Power Conditioning System (PCS) – This included the inverter that converts DC fuel power to AC.
4. Control System – All the thermal and electrical controls for smooth startup, steady-state operation, shut down and all safety logics were to be included here.
5. Hydrogen Purification – This included the compressor and Pressure Swing Adsorption units to purify hydrogen and deliver at 70 psig.

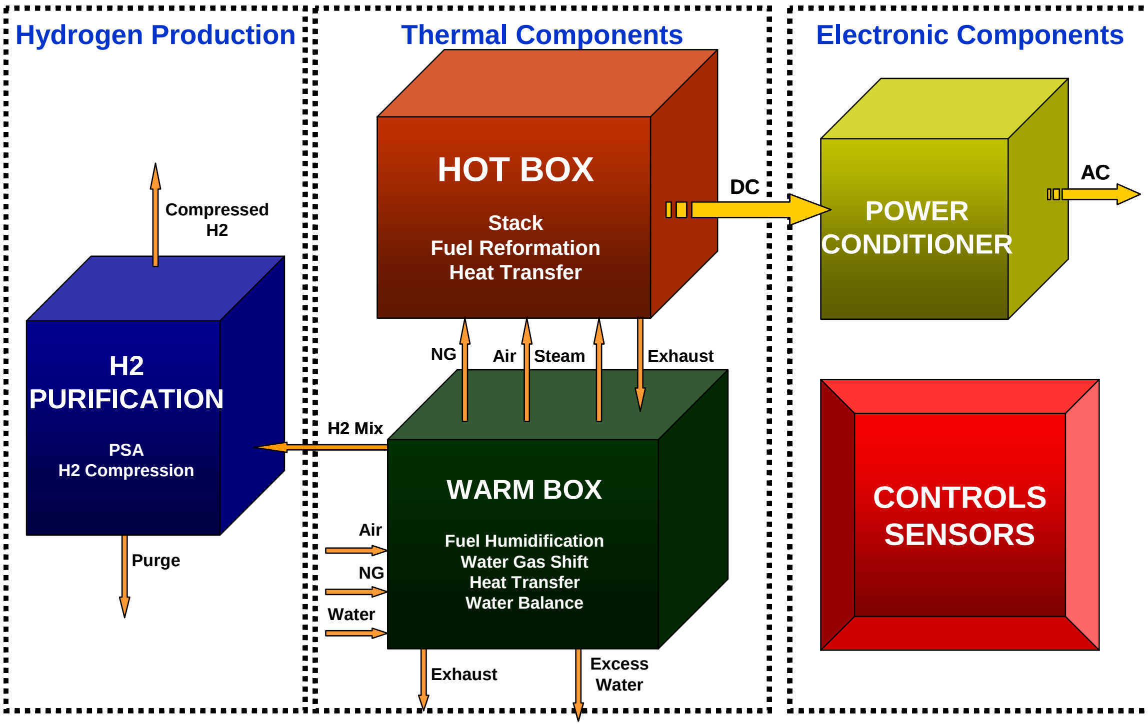


Figure 5. Overall system architecture.

Process simulation and optimization on the process flow diagram (PFD) was performed using ASPEN PLUS, a product of Aspen Technology, Inc. ASPEN flow sheets were split into sub models or "Hierarchy" models. The stack was simulated by a custom model which takes into account the complex reactions and electrochemistry. This model was integrated seamlessly within an ASPEN PLUS flow sheet. Process optimization was done using the Sequential Quadratic Program (SQP) algorithm available via ASPEN PLUS.

Natural gas is sent through a desulfurization unit and mixed with steam at a specific ratio of steam to carbon (typically with a molar ratio of 2 to 3) for steam methane reforming. The fuel gas – steam mixture is then sent into the "Hot Box". The anode exhaust coming from the "Hot Box" is fed to a shift reactor to reduce the concentration of carbon monoxide and shift this to hydrogen. Steam from the effluent stream is condensed and recycled back to the system to support reforming. The vapor from the condenser is fed into a compressor and PSA unit which separates pure hydrogen from the rest of the gases. Residual carbon monoxide is oxidized to avoid exhausting to the atmosphere.

The “Hot Box” is split into a fuel side and an air side. On the fuel side, the methane-steam mixture exchanges heat with the anode exhaust coming from the stack. The hot methane-steam mixture is fed into a reformer that is thermally coupled with the stack to effectively use heat rejected from the stack to support endothermic heat needed by the reformer. A portion of the steam-methane mixture can also be directly introduced to the stack to do internal reforming. This ratio (internally reformed to externally reformed methane) can be optimized for highly efficient thermal integration, taking the stack and electrode performances into account. Ion America has demonstrated electrode formulations which can operate with high ratios of internal reformation, but such formulations are not required for this system since external reformers will be sized to handle complete external reformation.

On the air side, outside air is blown into the hot box. Excess air is used to cool the stack. The air-side heat exchanger transfers heat from cathode exhaust to the inlet air.

Figure 6 shows a process flow diagram for the PSA system excluding the compressor. Note that the PSA was originally designed for purifying nitrogen from air. PSA was modified to purify hydrogen from the exhaust stream of the fuel cell. Figure 7 shows a photograph of the PSA unit with callouts noting some of the plumbing connections that were needed. Sorbents for the PSA were specified by Ion America and loaded by the PSA manufacturer (IGS Generon).

Figure 8 shows the flow schematic for the compressor that was used to compress the fuel cell exhaust for the PSA system.

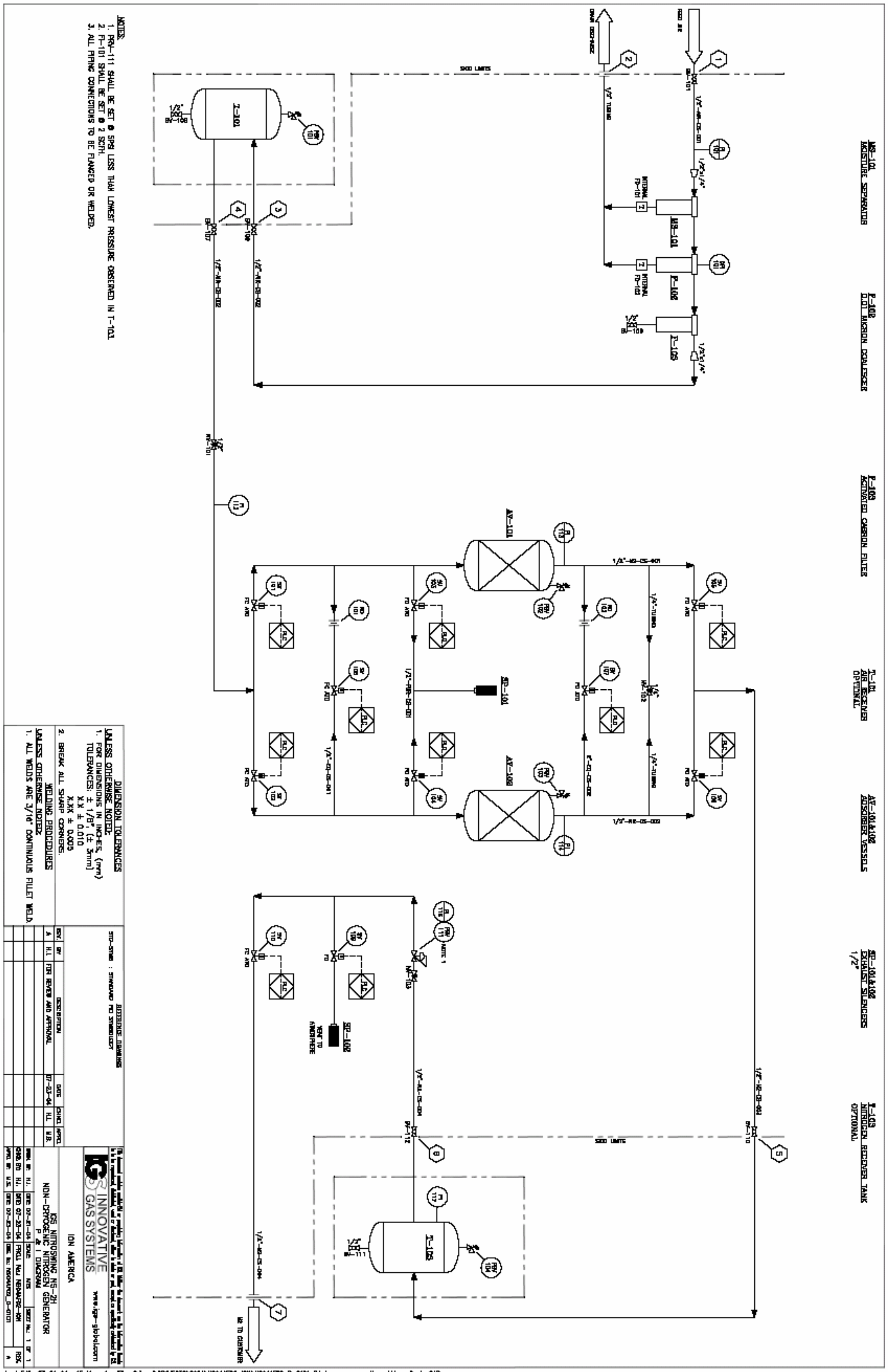


Figure 6. Flow diagram for PSA system excluding the compressor.

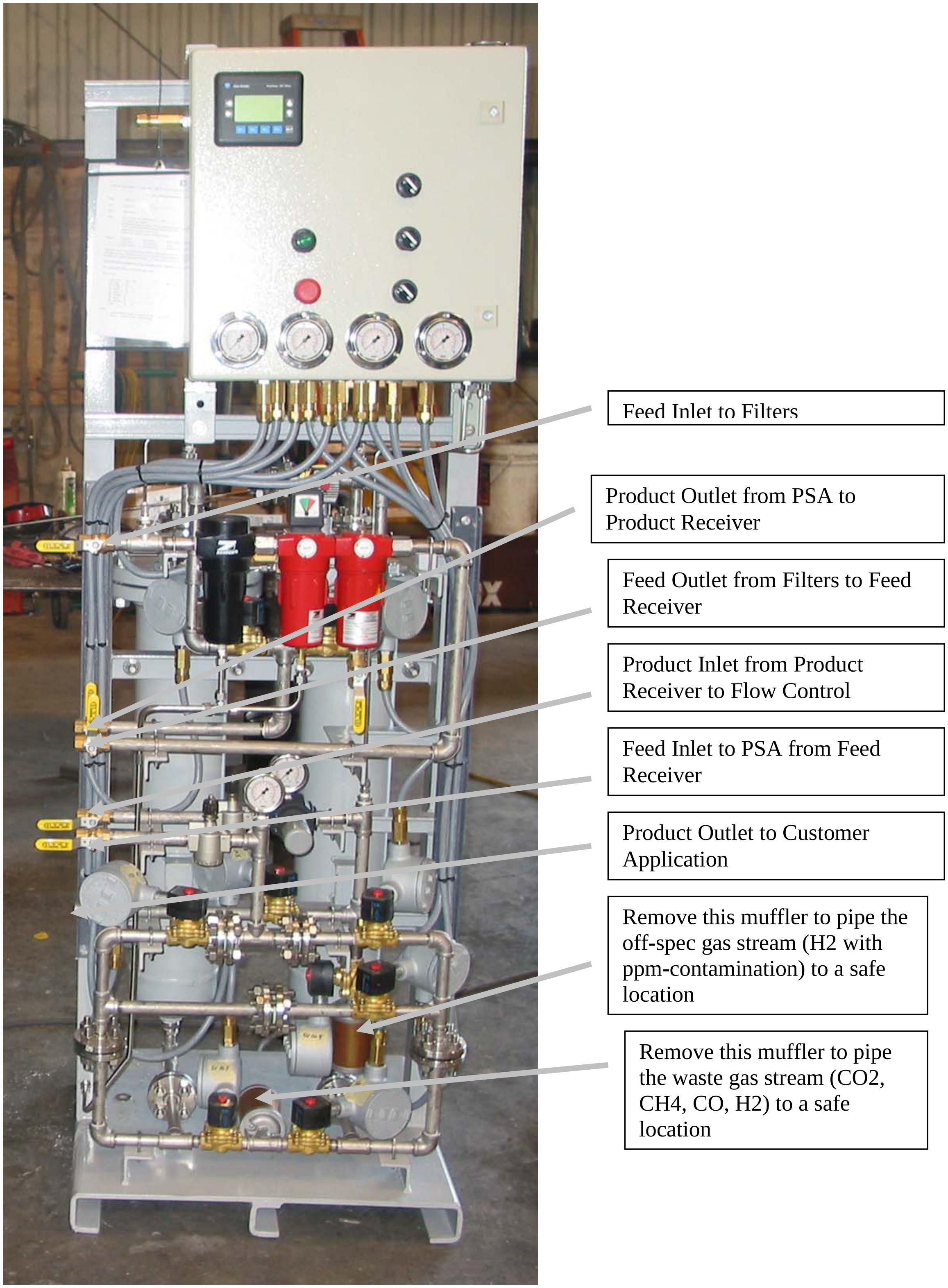


Figure 7. Photograph of the PSA system highlighting required plumbing modifications.

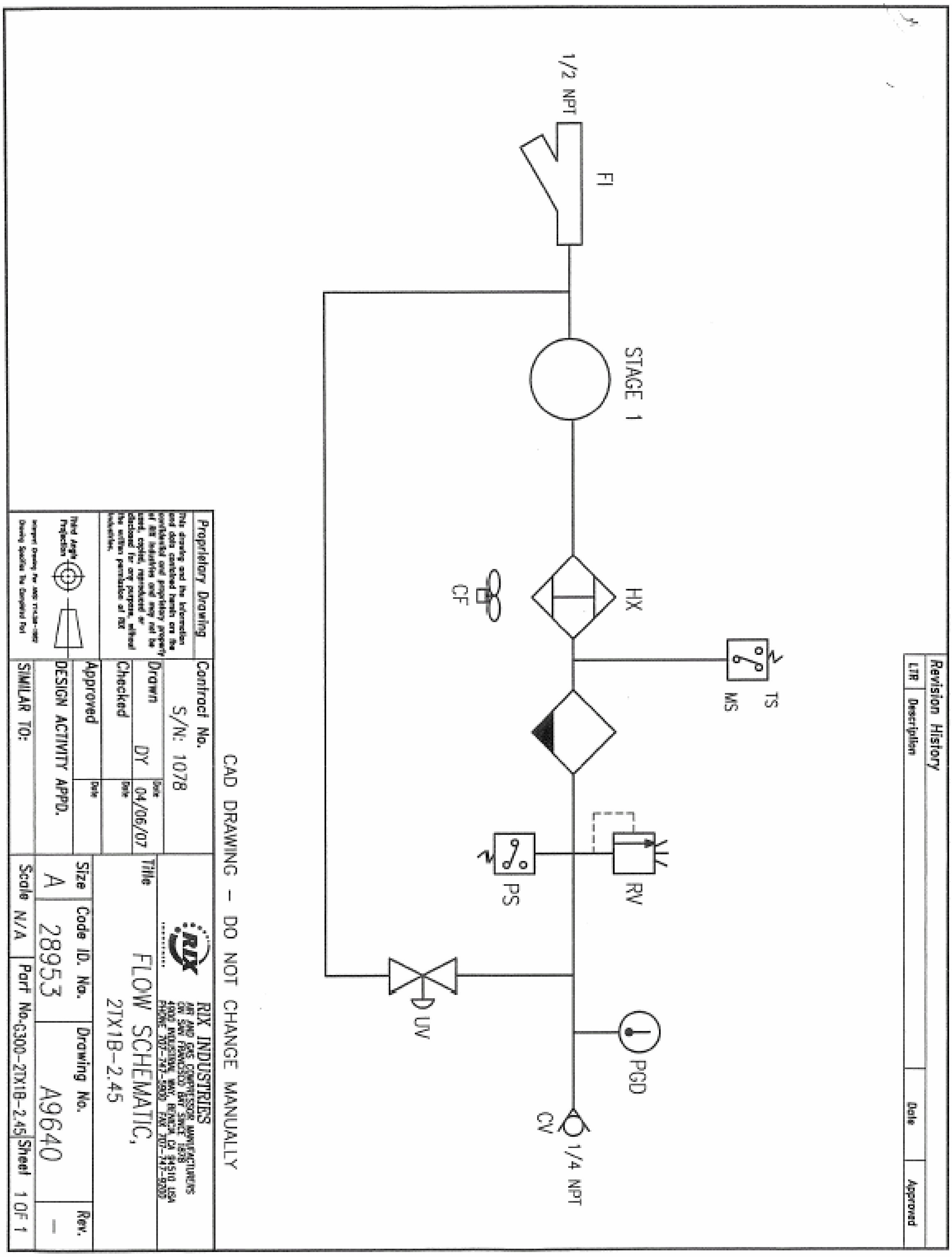


Figure 8. Flow schematic for exhaust compressor.

3.1.4. P&ID, Wiring Diagram, Communication Interface, and Power Budget update

A complete piping and instrumentation diagram (P&ID), for the Fuel Cell as well as the Hydrogen Purification System, was developed using AutoCAD.

A block diagram for the PCS system is presented in Figure 9. The 4 stages of the PCS included: input DC-DC converter, low voltage DC-AC converter, high voltage AC-DC converter, and output DC-AC converter. A high frequency (~10 kHz) isolation transformer was used to isolate the input from the output and to step up the low input voltage to the high output voltage.

Ion America also developed a communication interface using LabView platform. Ion America also partnered with Merlin CSI to develop a more cost-effective PC-based interface that emulated the LabView-based system. A block diagram for the controller is presented in Figure 10.

The analog input multiplexer layout for the distributed I/O is presented in Figure 11. It shows how I/O signals from the entire system were collected and processed to implement control logic for the system.

Communication Interface:
Ethernet interface, through an OPC server, enabled remote operation and monitoring of the system. Data for the system was collected and maintained in databases in order to study performance over time.

The 24 VDC safety system version 5 is presented in Figure 12. The safety system was independent of the control system. This was done to provide basic safety in the unlikely event of failure of the overall control system.

The Power Conditioning Unit consists of four separate converter stages:

1. Input DC-to-DC converter.
2. Low Voltage DC-to-AC Converter
3. High Voltage AC-to-DC Converter
4. Output DC-to-AC Converter

Isolation between the input and output stages is accomplished through a high frequency isolation transformer which also serves to step-up the low input voltage to high output voltage.

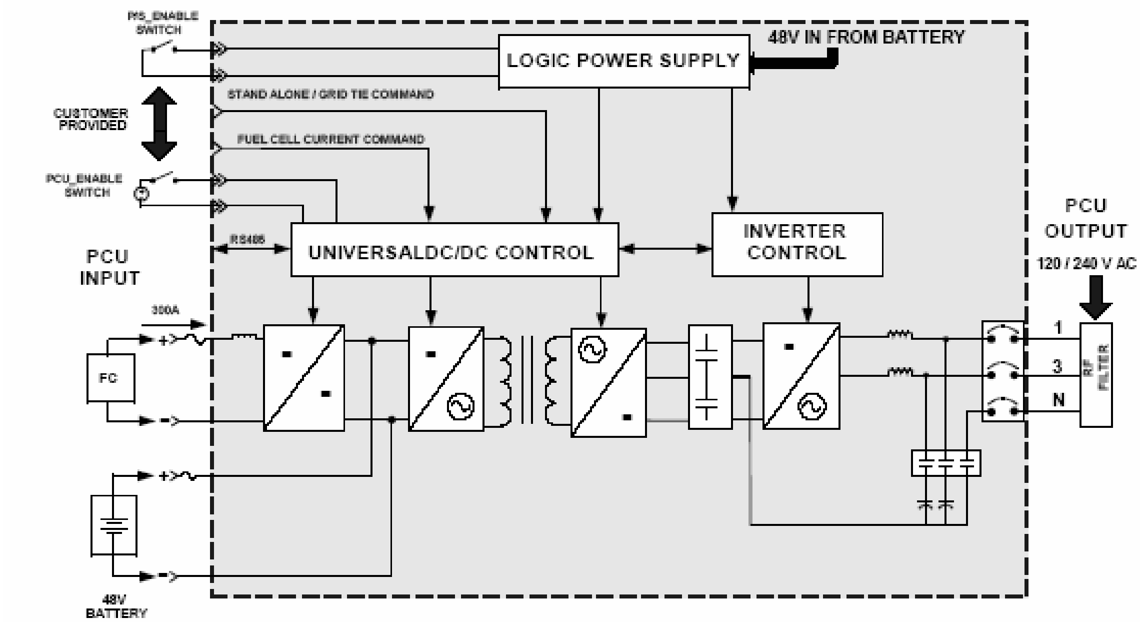


Figure 9. PCS block diagram.

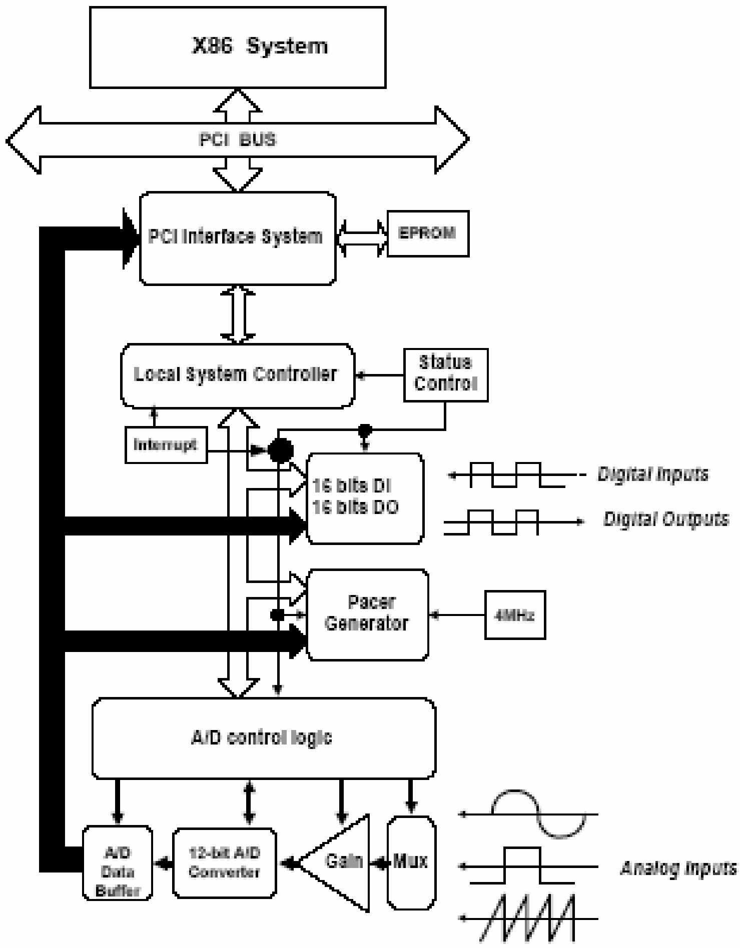


Figure 10. Controller block diagram.

The following is a list of general features for the PCI-1002 series.

• Bus: 5V PCI (Peripherals Component Interface) bus.

A/D:
• One A/D converter with maximum 110K samples/second.
• 32 single-ended / 16 differential programmable inputs for PCI-1002L/H.

DIO:
• 16 digital inputs and 16 digital outputs (TTL compatible).
• High speed data transfer rate: 2.7M word/sec (non-burst mode).

Timer:
• One 16-bit machine independent timer for software (Timer 2).
• Two 16-bit pacer timers for A/D converter and interrupt (Timer0, Timer1).

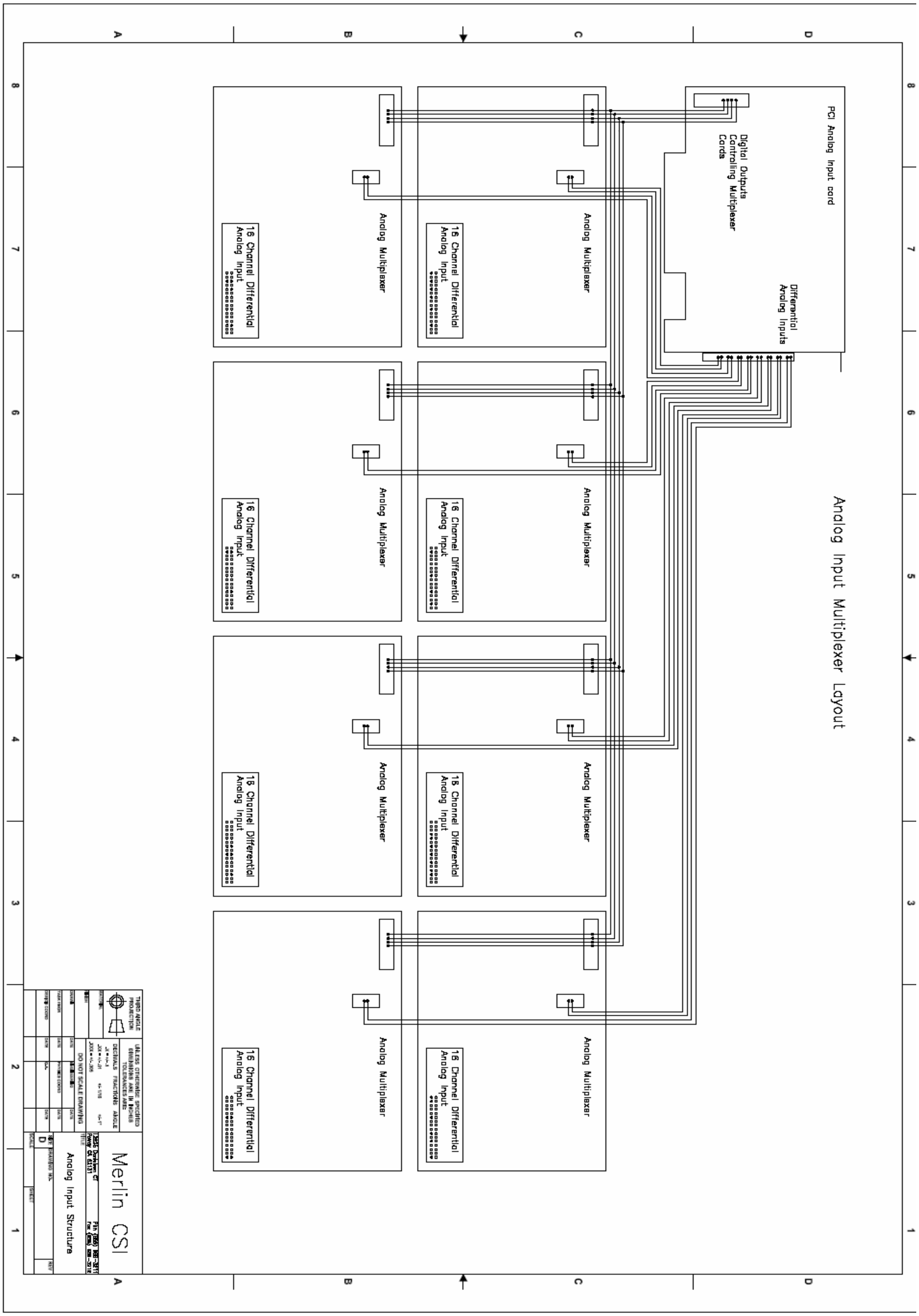


Figure 11. Analog input distributed I/O diagram.

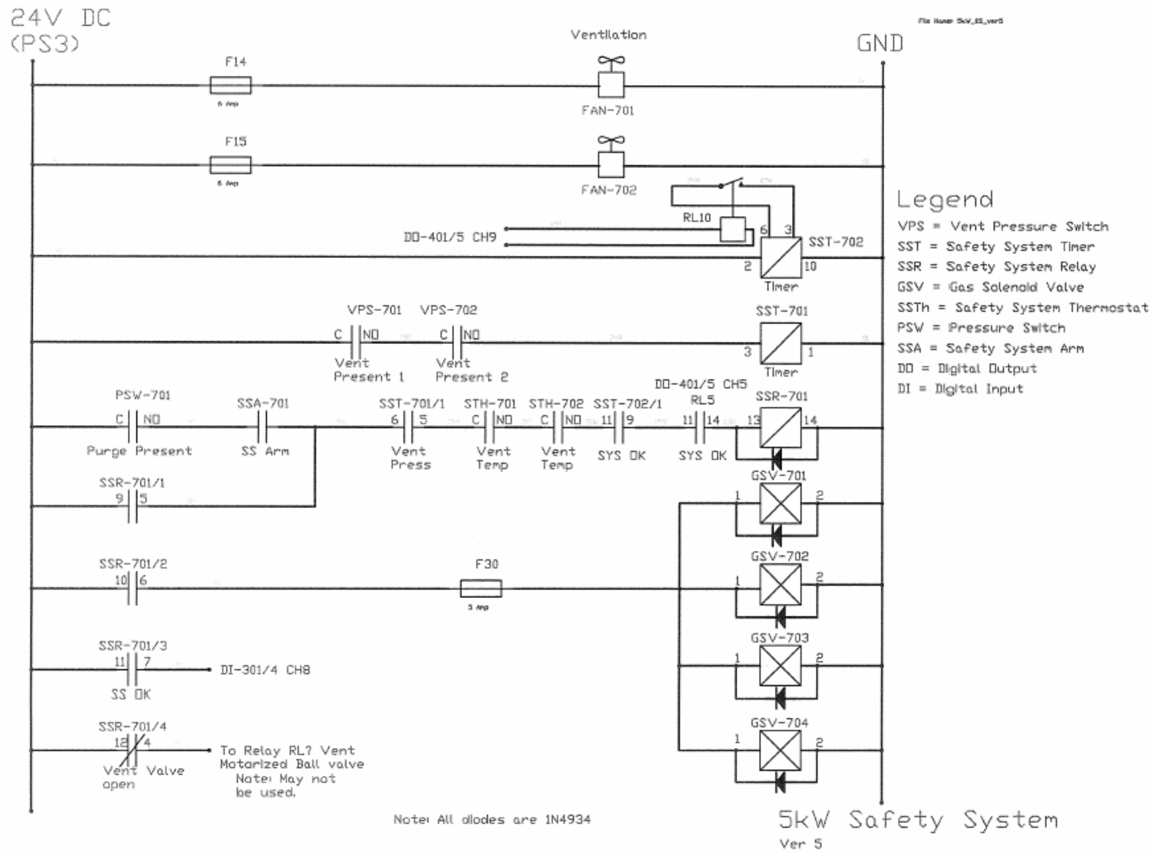


Figure 12. 24 VDC safety system version 5.

3.1.5. System performance projections

System performance projections were described in the January 2005 deliverable from IA to UTC and subsequently discussed with UTC.

3.1.6. System design freeze

The system design was frozen after reviewing with UTC.

3.2 Subsystem Design

Chemical compositions and thermal parameters were calculated at critical locations in the system. Enhancements were also made to the Control software during this phase. The Solid Oxide Fuel Cell (SOFC) stacks were designed and qualification tests were undertaken. The Balance of Plant (BoP) was also designed and its components procured.

Task 3.2 Milestones

3.2.1. Stack and Balance of Power (BoP) subsystem design completion
3.2.2. Control software change list
3.2.3. Subsystem design freeze

3.2.1. Stack and Balance of Power (BoP) subsystem design completion

The SOFC stack were designed to meet the system performance projections described in the "Task 3.1 System Definition – February 2005 Deliverable from IA to UTC". Qualification tests for various SOFC stack designs were undertaken. Ion America also engaged multiple vendors of stack components, and tested a range of cells with various performance and degradation characteristics, which allowed the selection of the best stack design.

The Balance of Plant (BoP) design was completed and the parts needed to build were procured. The procured BoP components were tested on a 5kW prototype SOFC system that is shown in Figure 13. The hotbox was redesigned to accommodate 50-cell stacks, instead of 25-cell stacks.

Figure 14 shows a photograph of the hydrogen purification subsystem. The PSA was originally designed for purifying nitrogen from air and was modified to purify hydrogen from the anode exhaust stream of the fuel cell. Sorbents for the PSA were specified by Ion America and loaded by the PSA manufacturer (IGS Generon).

Figure 13. Prototype 5 kW SOFC system used to qualify subsystem designs.

Figure 14. Photograph of the hydrogen purification system tested at Ion America.

3.2.2. Control software change list

Ion America developed a LabView-based communication interface. The control software was tested on the 5 kW SOFC system used to qualify subsystem designs. Enhancements to the control software were made along the way.

3.2.3. Subsystem design freeze

By the end of the step, most of the subsystem designs were frozen in order to procure parts for qualification tests.

3.3 Component and Subsystem Test

As a part of this step, a detailed Bill of Materials and special vendor requirements were prepared. Component and subsystem test equipment was also set up and system control software upgrades were implemented. Component and subassembly tests for Quality Control and performance verification were completed. All of the critical goals of this task were completed by the end of July 2005. However, Ion America chose to continue this task through August to allow an additional end-to-end system test with updated components, control software, and the inverter in the loop. The end-to-end system test successfully validated all components of the 5 kW system, and the system achieved 5.1 kW DC from the stacks on August 26, 2005 at 11:32 AM. The PSA system was run as a separate test using simulated anode exhaust. The PSA demonstrated <10 ppm of CO, which is the threshold limit for CO of the online gas analyzer, and adequate for use in PEM systems. Other impurities (CO_2 and CH_4) were also reduced to acceptable levels for use in PEM systems.

Task 3.3 Milestones

3.3.1. Complete Bill of Materials
3.3.2. Vendor requirements definitions
3.3.3. Test equipment setup and system control software upgrades
3.3.4. Complete component and subsystem test

3.3.1. Complete Bill of Materials

A Bill of Materials (BoM) was specified and captured in Agile Product Lifecycle Management (PLM) software. Hardware for the PC-based control system was received in August 2005.

Several important improvements were made to increase electrical output, increase efficiency, and prolong the operational life of the system. Those improvements are described below:

> 1 – A high precision, non-invasive, water flow meter was added to the system, in order to continuously monitor the critical steam-to-carbon ratio in the system. The simple water flow switch, from the original design, was replaced by an ultrasonic water flow meter. The ultrasonic water flow meter provided excellent feedback for the end-to-end system test. Use of this flow meter identified a control problem with the water metering pump and likely kept the system test from running at a critically low steam-to-carbon ratio that could have caused coking.

> 2 – Net-Shaped (NS) Interconnects (ICs) were identified for use in the SOFC stacks. The use of NS ICs reduced the cost, improved reliability, and made the air and fuel flow more uniform throughout the stacks, compared to machined ICs.

Improved uniformity enabled the operation with higher utilization of reactants, thereby increasing the efficiency.

3 – Higher performing electrolytes were also identified for use in the stacks. The higher performing electrolytes enabled higher electrical output and increased efficiency at a fixed electrical output for each SOFC cell.

4 – Electrode formulations were also qualified to demonstrate compatibility with the higher performing electrolytes and NS ICs.

5 – Improvements were made to the reformer/combustor to enable more uniform light-off at lower temperatures. Validation testing of the new reformer/combustor design was completed in July 2005. The reformer/combustors to be used in the Chattanooga system were received and integrated in August 2005.

6 – Minor modifications were also made to enable recycle of hydrogen back into system (in the event the hydrogen is not needed at the UTC site). This enabled higher efficiencies in non-hydrogen producing mode. This modification required a hydrogen line going from the PSA, situated on the pad outside the Fuel Cell Test Facility, back into the main 5 kW system.

7 – The state machine and FMEA were also updated based on results of the end-to-end system test performed in August 2005. A state machine with FMEA driven PC-based control system provided more stable operation, which was easier to control.

8 – IA also commenced a test program to make the system more robust for shipping long distance. A mock hot box was fabricated with “dummy stacks” that had similar weight and form factor to real stacks. A single real stack with current lead attached was inserted in the build, along with key compression elements, manifolding, thermocouples, with a section of the warmbox components. Accelerometers were attached to several components within the mock hotbox, in order to measure response to a vibration load profile that mimics shipment on an air ride trailer. Testing occurred in August and was done in conjunction with a company that designs packaging for delicate equipment. Packaging for the 5kW hotbox was designed based on results from these tests.

3.3.2. Vendor requirements definitions

Most vendor requirements were defined and captured in Agile PLM. The CAD drawing package was captured and continuously updated in SolidWorks.

3.3.3. Vendor requirements definitions

Most vendor requirements were defined and captured in Agile PLM. The CAD drawings were converted into SolidWorks.

3.3.4. Test equipment setup and system control software upgrades

An end-to-end system test of the hot box (including SOFC stacks), warm box, and LabView control system was performed in May 2005. Data from the May tests were collected, and analyzed. Several improvements were made to system components and to control algorithms used in the state machine. An update was ready in time for the end-to-end system test (including the PCS) that commenced in August 2005.

Ion America partnered with Merlin CSI to develop a PC-based control system that mimicked the LabView-based control system.

The hydrogen purification system was modified to run in a recirculation mode, whereby the purified gas and the effluent purged gas are recombined in a fourth buffer tank, in order to get additional run time out of each cylinder of simulated anode exhaust gas. The basic process flow for the hydrogen purification system is shown in Figure 15. The process flow for the hydrogen purification system with modifications for recirculation is shown in Figure 16.

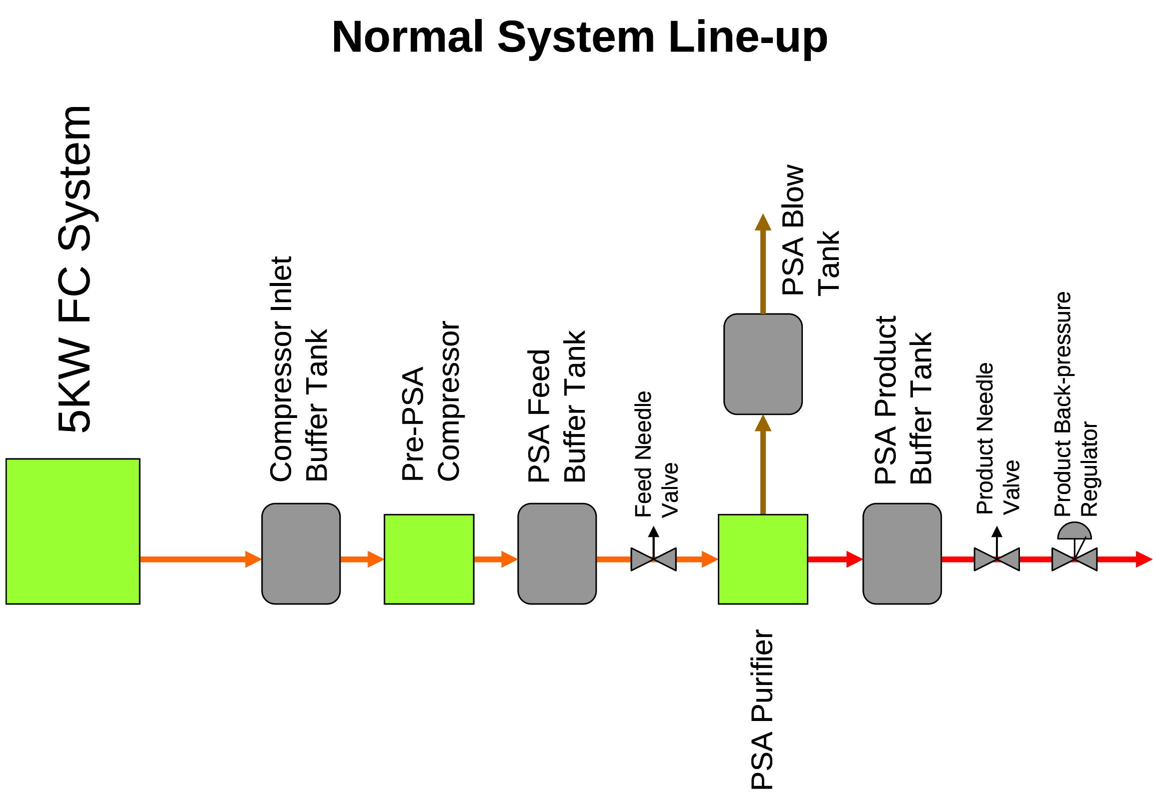


Figure 15. Basic process flow for the hydrogen purification system.

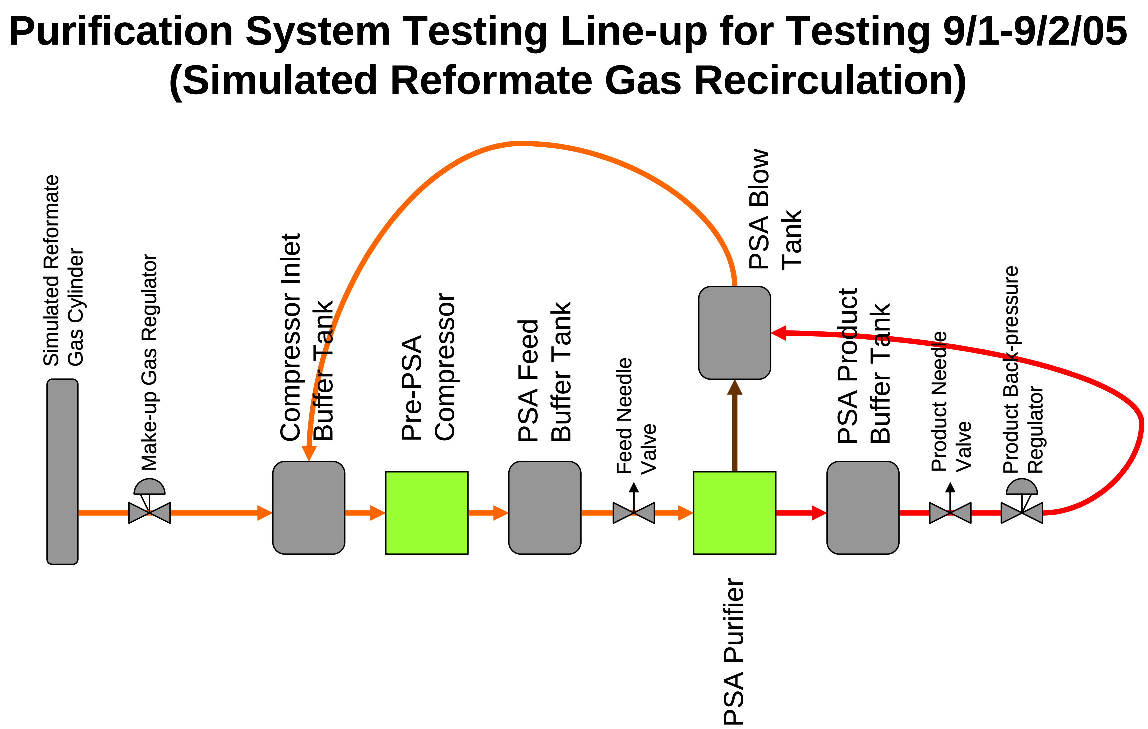


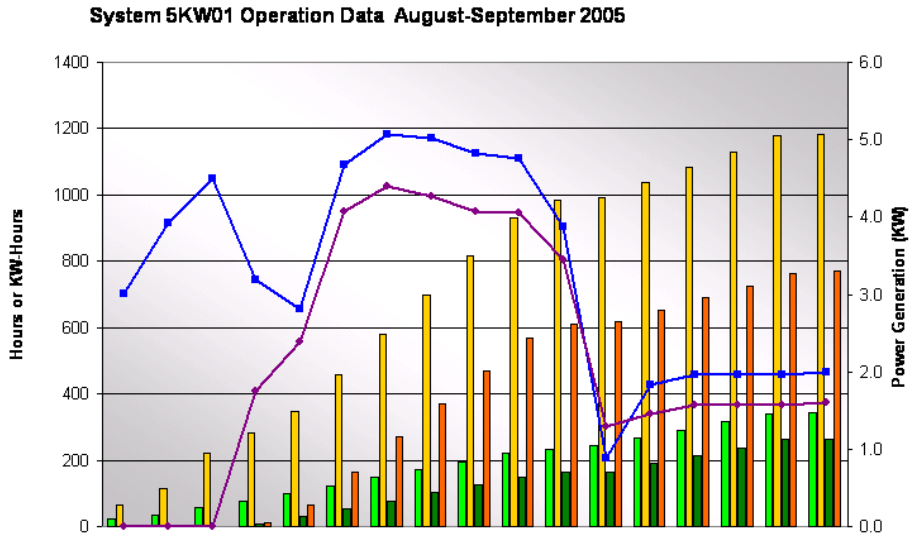
Figure 16. Process flow for the hydrogen purification system with recirculation.

3.3.5. Complete component and subsystem test

An end-to-end system test commenced on August 19, 2005, which successfully validated all components of the 5 kW system. The system achieved 5.1 kW gross DC output from the stacks on August 26, 2005 at 11:32 AM.

Figures 17 and 18 show the system data for the first 343 hours of operation (through 9/6/05). It shows running hours, running kWh, running inverter hours (power exported to the grid), running inverter kWh, average stack power, and average inverter power.

Figure 19 shows the excellent water flow feedback provided by the ultrasonic water flow meter. This feedback helped in the design of better control of the critical steam:carbon ratio.



	8/21	8/22	8/23	8/24	8/25	8/26	8/27	8/28	8/29	8/30	8/31	9/1	9/2	9/3	9/4	9/5	9/6
Running Hours Total	22	34	58	77	100	124	148	172	196	220	233	244	268	292	316	340	343
Running KW-hours total	66	114	222	281	346	458	579	700	816	930	983	992	1036	1083	1130	1177	1183
Running Inverter Hours Total	0	0	0	6	29	53	77	101	125	149	163	166	190	214	238	262	265
Running Inverter KW-hours total	0	0	0	11	66	164	269	372	470	567	612	616	651	689	726	764	769
Average Stack Power	3.0	3.9	4.5	3.2	2.8	4.7	5.1	5.0	4.8	4.8	3.9	0.9	1.8	2.0	2.0	2.0	2.0
Average Inverter Power	0.0	0.0	0.0	1.7	2.4	4.1	4.4	4.3	4.1	4.1	3.4	1.3	1.5	1.6	1.6	1.6	1.6

Figure 17. 5kW-01 system data for the first 343 hours of operation.

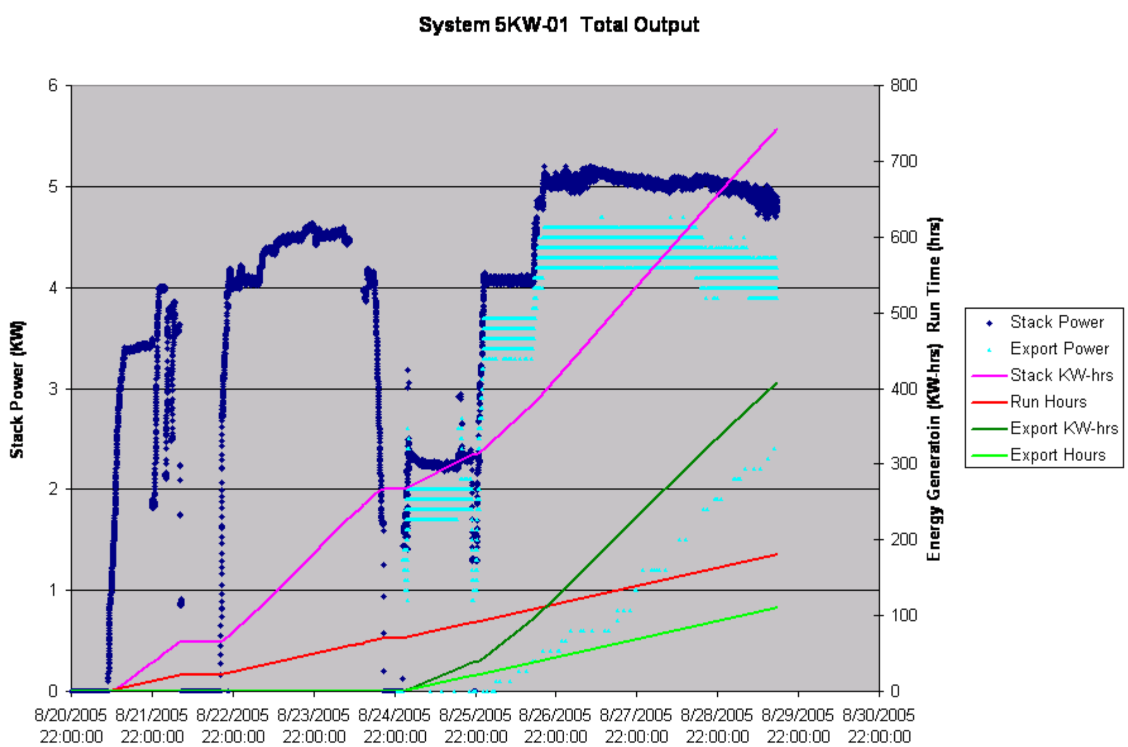


Figure 18. 5kW-01 system data for the first 343 hours of operation.

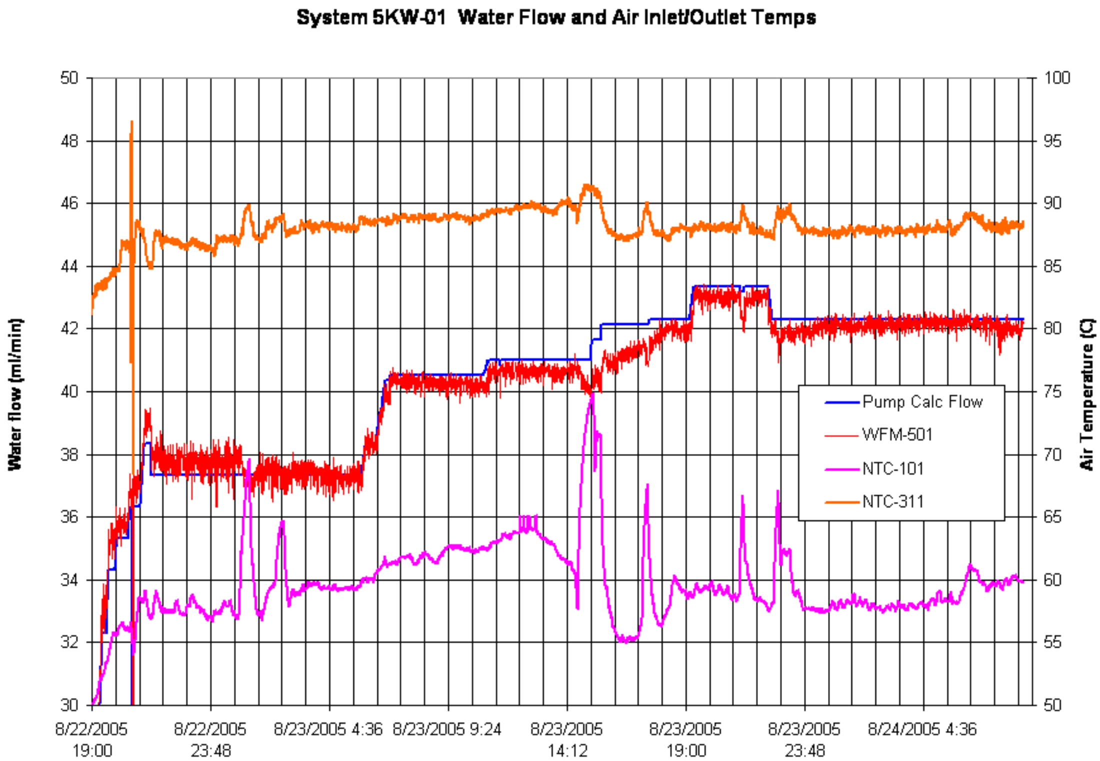


Figure 19. Demonstration of excellent water flow feedback provided by the ultrasonic water flow meter.

The PSA system with recirculation was run as a separate test using simulated anode exhaust. The PSA hydrogen purity is shown as a function of time for experiments run on September 1, 2005, in Figures 20 – 22.

Hydrogen purity from the PSA system demonstrated <10 ppm of CO, which is the minimum detectable limit for CO concentration in the Online Gas Analyzer (OGA), and is adequate for use in PEM systems. CO_2 and CH_4 concentrations were also reduced to acceptable levels for use in PEM systems. A screenshot from the OGA with 50 ppm CO_2, 10 ppm CH_4, and <10 ppm CO, is shown in Figure 23.

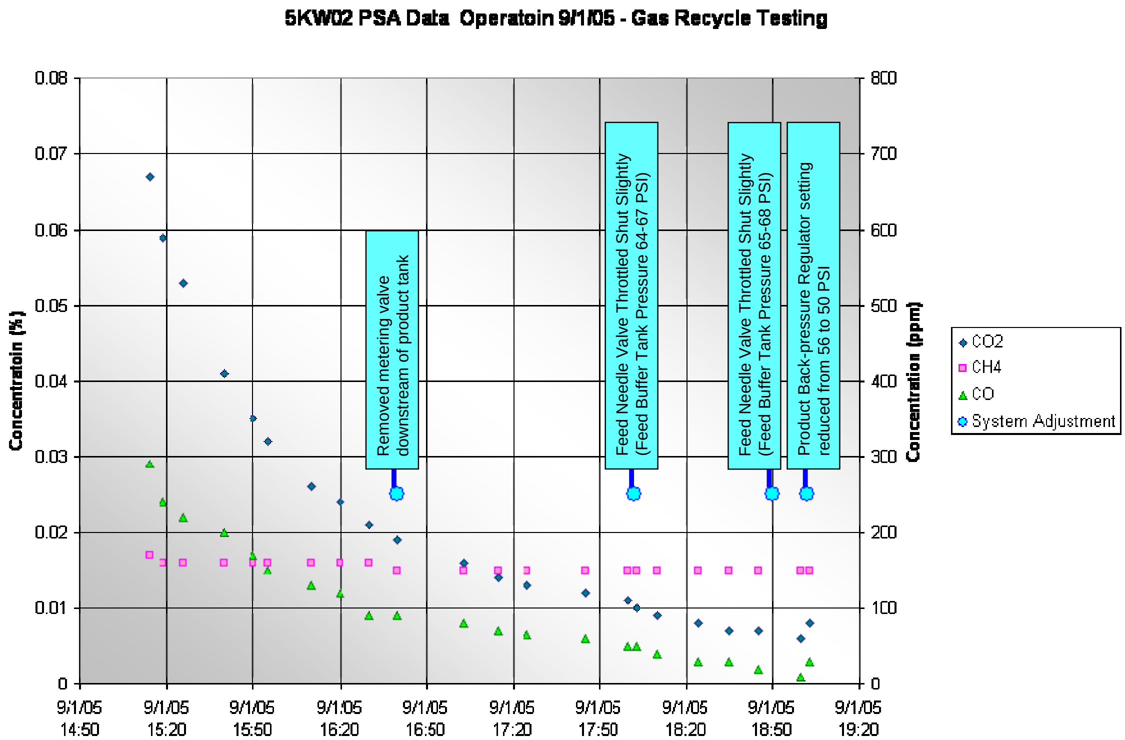


Figure 20. Hydrogen purity (impurity concentration) as a function of time on 9/1/05.

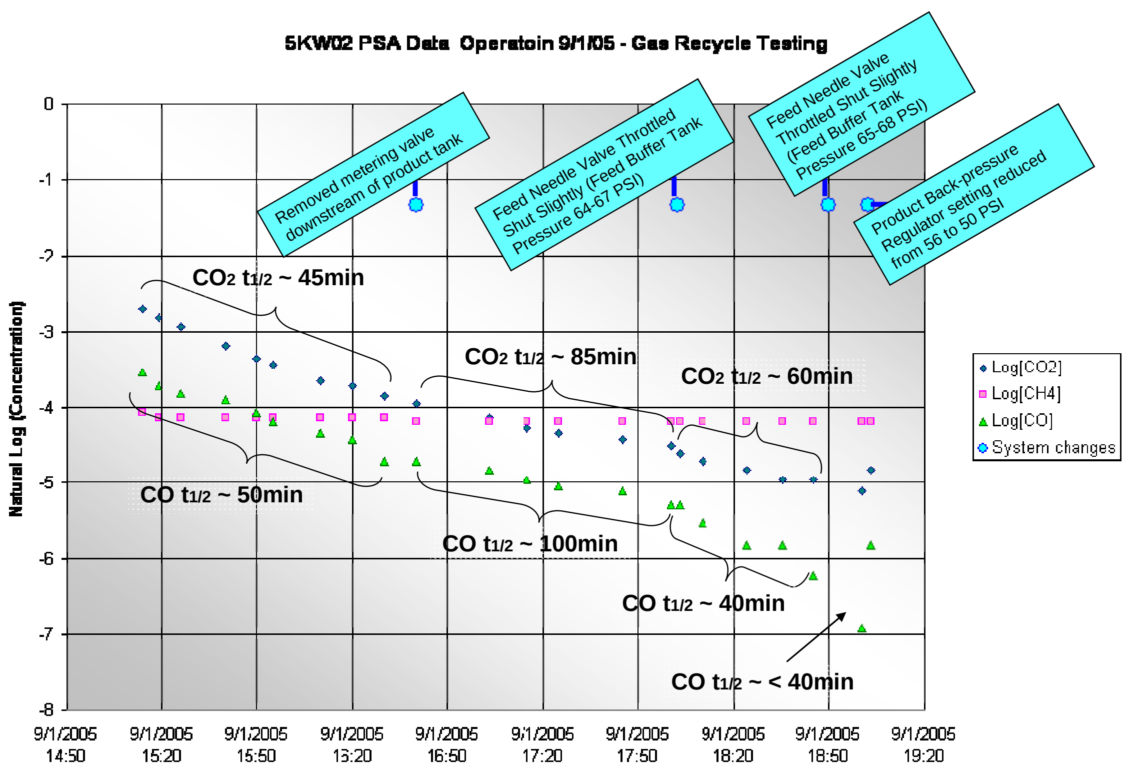


Figure 21. Hydrogen purity (natural log of impurity concentration) as a function of time on 9/1/05.

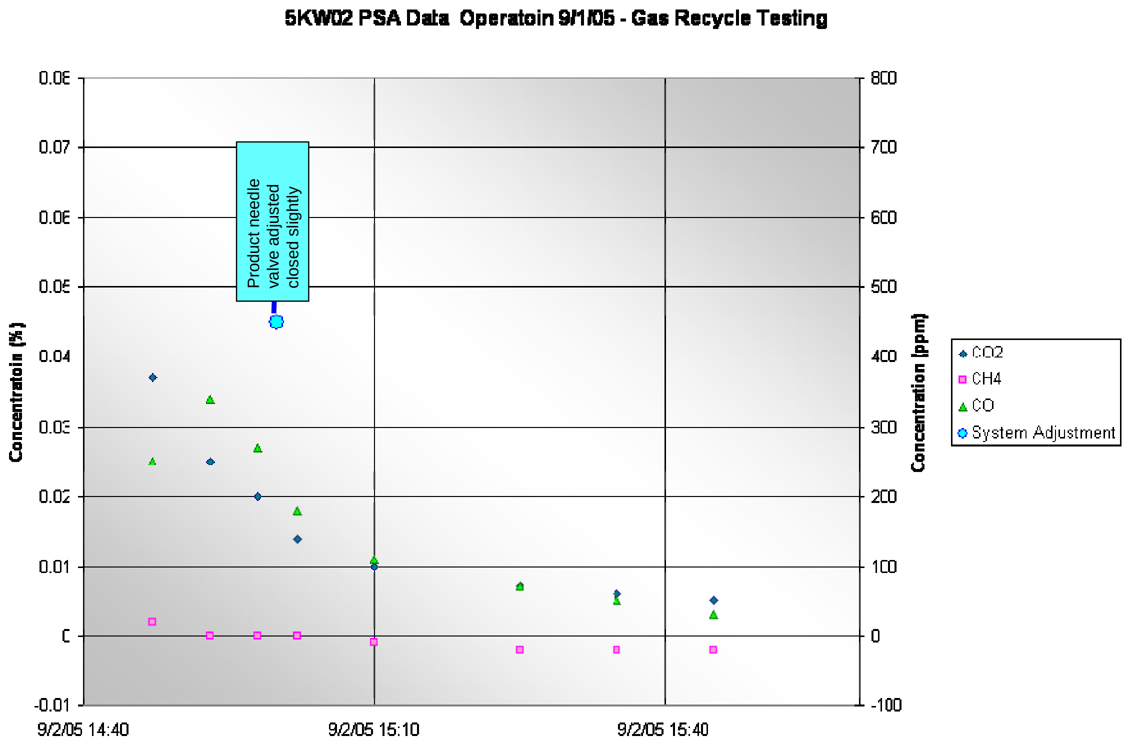


Figure 22. Hydrogen purity (impurity concentration) as a function of time on 9/2/05.

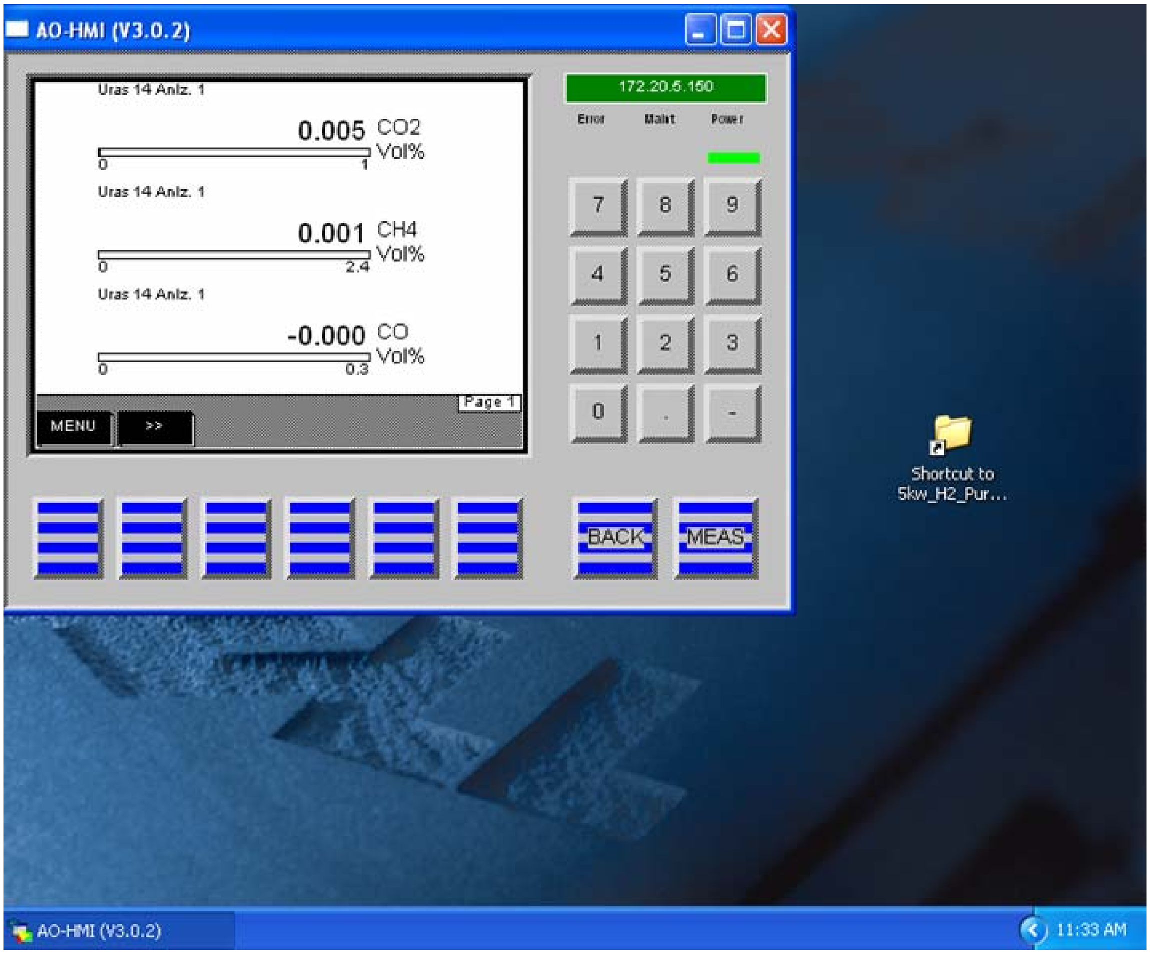


Figure 23. OGA screenshot on 9/9/05 at 11:33AM PDT shows hydrogen with 50 ppm CO_2, 10 ppm CH_4, and <10 ppm CO (below detectable limit for OGA), which is adequate purity for PEM fuel cells.

3.4 Stack Assembly

Stack component and cell assembly was completed. Electrolytes were manufactured first, with electrode layer deposition and firing next. Finally, cell stacking and final stack assembly were completed with the maximum degree of automation feasible within the contract time frame. The sixteen 25-cell stacks for the hot box assembly used Net-Shaped (NS) Interconnects (ICs) and higher performing electrolytes made from Scandia Stabilized Zirconia (SSZ), instead of Yttria Stabilized Zirconia (YSZ). Electrode formulations were qualified to demonstrate compatibility with the SSZ electrolytes and NS ICs.

Single cell, 10-cell, and 25-cell stacks were fabricated and tested using various configurations. An optimized configuration was selected, and qualified stacks were fabricated. After qualification, sixteen additional cell stacks were individually tested and delivered in September 2005.

<u>Task 3.4 Milestones</u>

3.4.1. Electrolyte manufacturing
3.4.2. Electrode manufacturing
3.4.3. Cell stacking
3.4.4. Stack completion

3.4.1. Electrolyte manufacturing

Cell testing with various electrolytes has been ongoing since the program's inception. IA performed extensive screening of electrolytes made in-house and by several different vendors. Electrolytes for this program were initially going to be made from YSZ, because of the extensive database of performance characteristics that IA has developed over the past 3 years. Although IA had tested higher performing electrolytes made from SSZ, most of this work has been limited to the past ~1 year. The SSZ electrolytes were considered to be high programmatic risk if delivery of the system was required in September 2005. After reviewing the impact of several improvements to the system, including the use of higher performing electrolytes, IA agreed to refocus its efforts on using SSZ this summer.

IA made a downselect to two candidate electrolyte vendors that were being considered for manufacturing electrolytes for the Chattanooga system, and worked with the vendors to improve quality and uniformity. Qualification SOFC stacks were manufactured using SSZ electrolytes from both vendors. After reviewing test results, IA selected one of the two electrolyte vendors and completed qualification of their as-fired SSZ electrolytes for the Chattanooga system.

3.4.2. Electrode manufacturing

IA qualified electrodes (anodes and cathodes) for cells using YSZ and SSZ electrolytes. IA has extensive history with machined YSZ electrolytes, machined ICs, and electrodes optimized for that material set. IA had been moving towards qualification of lower cost/higher performing cells using as-fired SSZ, net-shaped ICs, and electrodes optimized for the newer material set. Qualification SOFC stacks using different electrode configurations were built and tested. Various thicknesses, chemistries, and contact layers were tested in order to optimize performance and stability. Electrode qualification was completed for the SOFC stacks to be used in the Chattanooga system.

3.4.3. Cell stacking

After screening various configurations of cell stacks using different electrolytes, ICs, and electrodes, IA chose a configuration using lower cost/higher performing cells with as-fired SSZ electrolytes, net-shaped ICs, and electrodes optimized for the newer material set. After successful qualification of the SOFC stacks using the desired configuration, sixteen 25-cell stacks were fabricated and individually tested to verify performance. The cell stacks were completed in September 2005.

3.4.4. Stack completion

IA completed the manufacturing of the stacks for use in the Chattanooga system. Since IA wanted to ensure a successful demonstration at the UTC site, a spare set of stacks was manufactured.

Other accomplishments in September 2005

- All BoP components were ordered and received. Assembly of the final system was 75% completed.

- The successful end-to-end system testing on 5kW-01 (Figures 24 – 28) with and without PSA connected was completed and provided a basis for successful operation of the 5kW-02 system that IA delivered to UTC. Several key differences between the 5kW-01 (temporary system configuration) and the 5kW-02 (permanent system configuration to be delivered to Chattanooga) are shown in Figure 29.

- IA also worked on repackaging the hydrogen purification system in a box that is ~4' x 8' x 5' high. The new package, besides being shippable, also helped reduce the noise of the hydrogen purification components.

- IA also worked with UTC to draft site preparation drawings for the UTC Fuel Cell Test Facility and for the electrical interface module that provided interface between the fuel cell and the grid. These drawings are included in the Appendix.

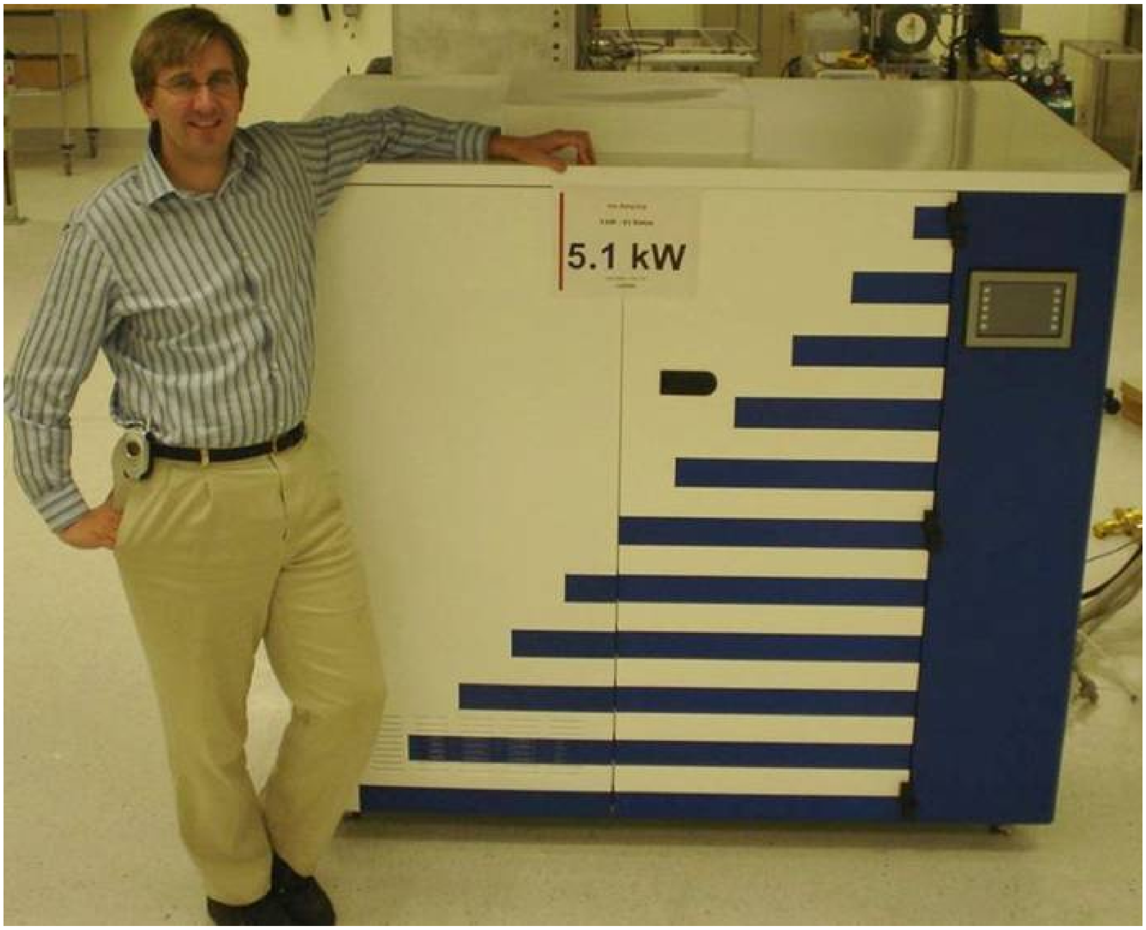


Figure 24. Picture of 5kW-01 system with painted enclosure.

System Operation:

- Started drawing power at 2:00 am on August 21st
- Completed **820** hours of operation on Sep 28th
- Produced **1893** kWh of DC power
- Sent **1261** kWh of AC power to the "grid"
- Achieved **94**% system availability
- Achieved peak DC power of **5.1** kW
- Recorded peak system (AC Power + Hydrogen) efficiency of **44**%
- Recorded uniform temperature and current profiles among columns

Controls:

- System startup completely automated (State Machine)
- Fully operational FMEA software and corrective actions in place
  - (e.g.) Detected NG pressure loss and went into safe shut down
- State Machine and FMEA code can be updated and loaded while the system is running
  - Unique in the fuel cell industry – Invention disclosure filed

Hydrogen production:

- Successfully operated the hydrogen purification system with main unit
- Recorded high hydrogen purity (<**10** ppm of CO) and yield (>**80**%)

Figure 25. Summary of 5kW-01 system operation, controls, and hydrogen production.

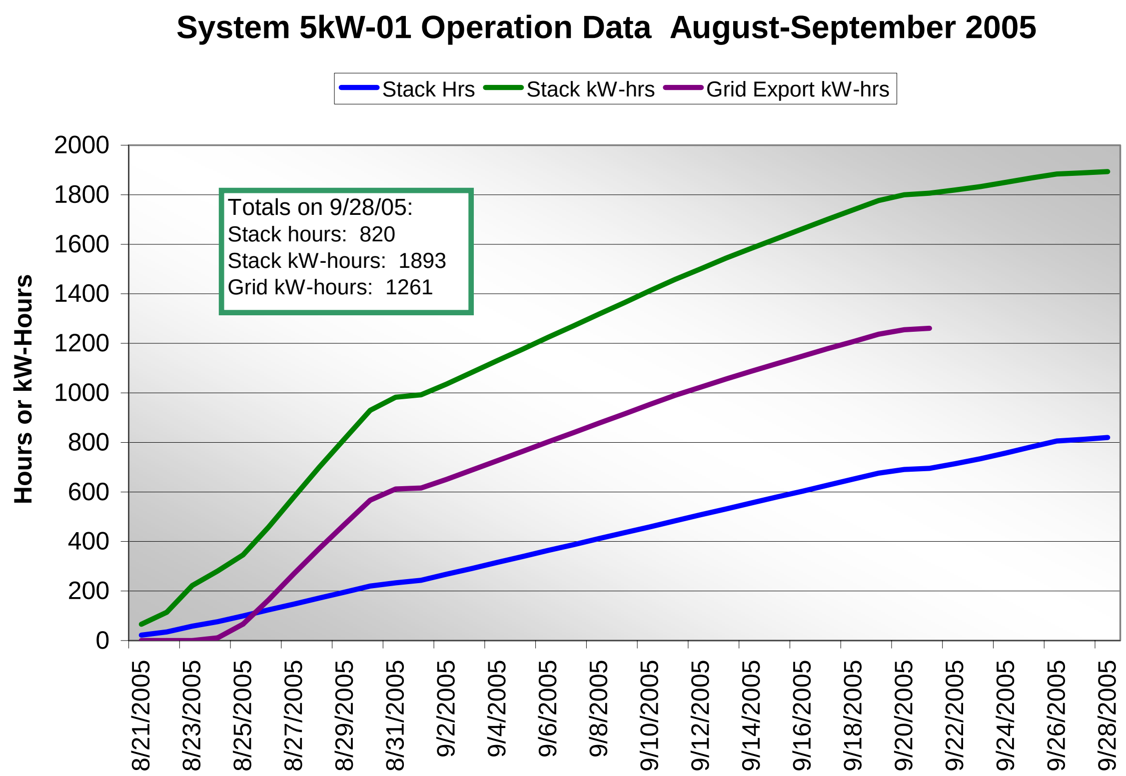


Figure 26. 5kW-01 system operation data.

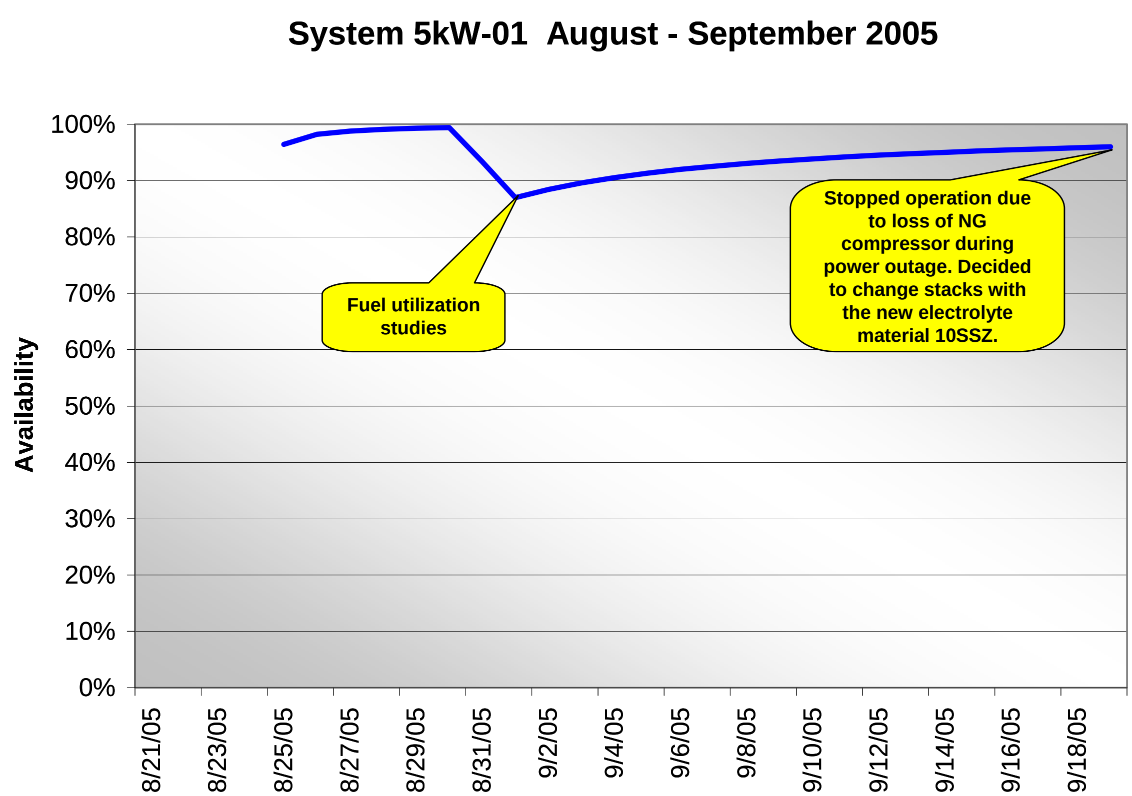


Figure 27. 5kW-01 system availability data.

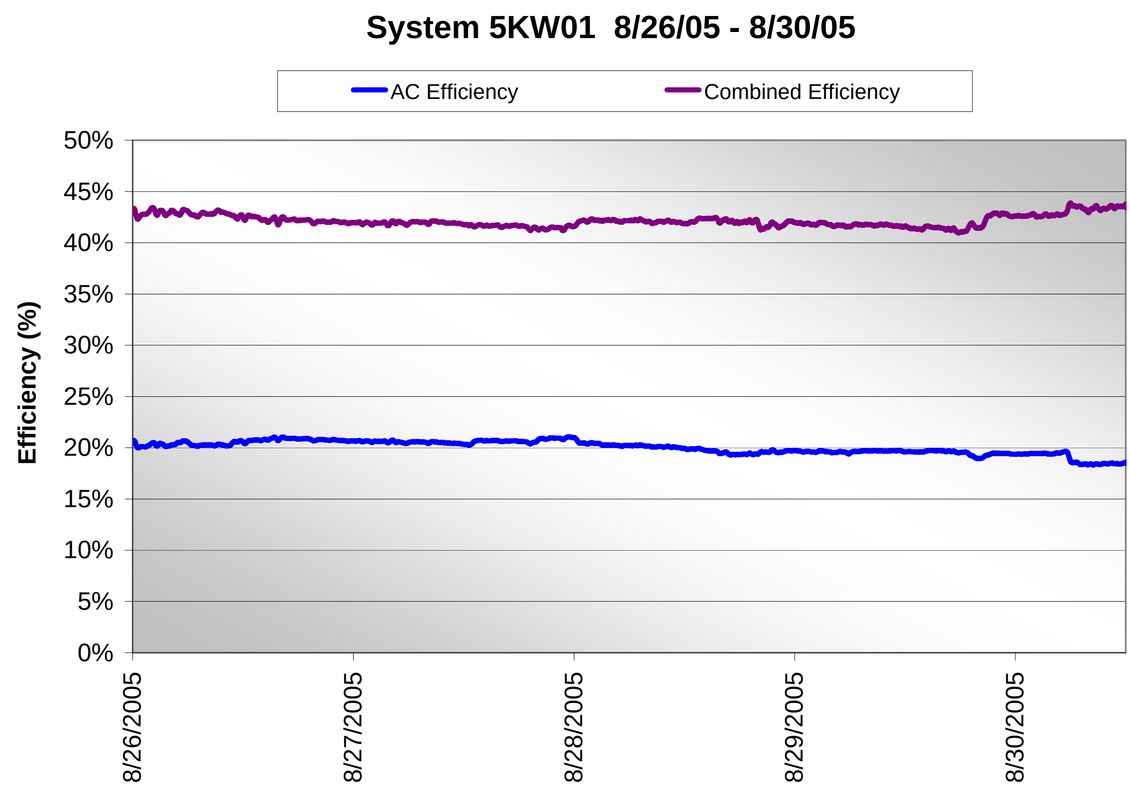


Figure 28. 5kW-01 system efficiency data.

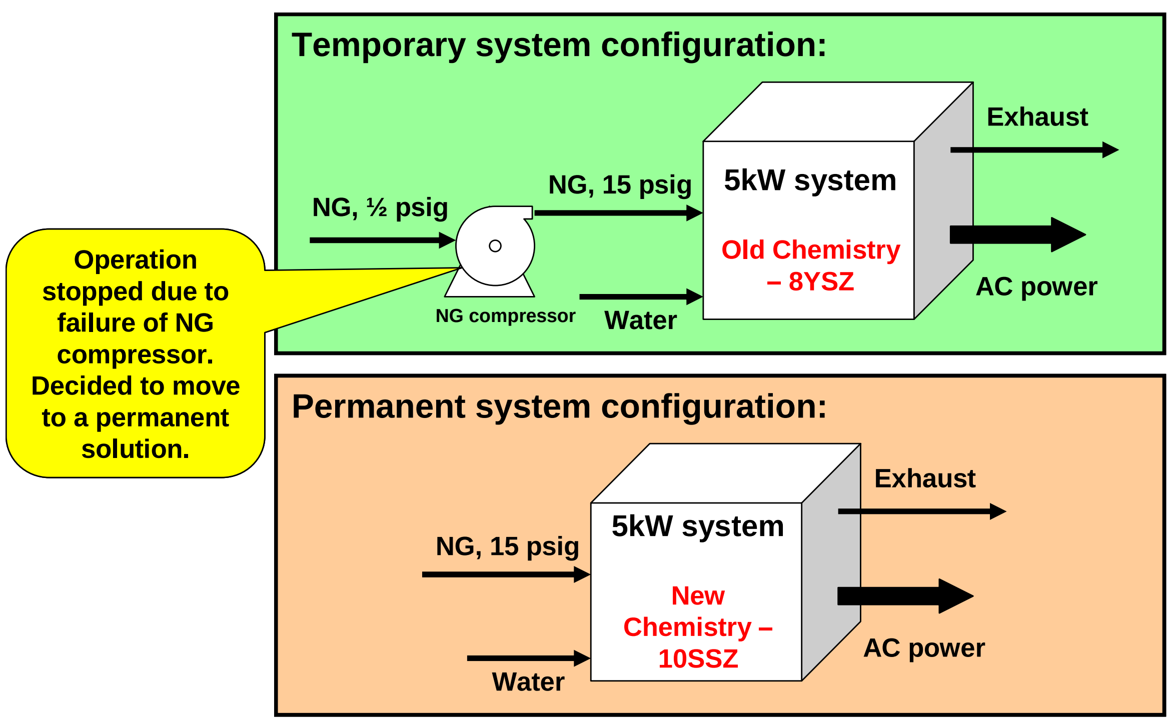


Figure 29. 5kW-01 (temporary system test configuration) compared to 5kW-02 (permanent system configuration).

3.5 Balance of Plant Assembly

Balance of Plant assembly was completed for the 5kW-02 system. All components of the main system were installed, assembled, and wired. The sixteen 25-cell stacks for the hot box were assembled and installed into the system after completion of testing with dummy stacks at the end of October 2005. The hydrogen purification system was repackaged into an enclosure.

Initial testing of the 5kW-02 system commenced in November 2005 and 4.6 kW was demonstrated in early operation at relatively low temperature (~800 C) and relatively high electrochemical efficiency (0.8V/cell). The system was operated with the inverter in grid tie mode, and up to 4 kW (208V/3P) power was exported to the grid.

3.6 System Test

Each of the sixteen 25-cell stacks for the hot box assembly was tested on a 50-cell test stand to verify performance prior to installation into the 5kW-02 system. After commissioning, the sixteen 25-cell stacks were installed and the system was started.

The system initially produced DC power on 11/19/05 at 17:30 PST, and a series of tests were performed. Stand-alone (off-grid) testing was performed to verify the Balance of Plant (BoP), power, and computer control functionality. The system response to load steps was also verified, and control system fault response tests were performed. By 08:30 AM PST on 12/19/05, the system had run for 674 hours with 95% availability.

The hydrogen purification system was repackaged and subsequently tested using anode exhaust directly from the 5kW-02 system to verify the new automated compressor control. Ion America hosted visits by Don Eberhart (UTC) on December 6-7, 2005, and Jason Hixson (UTC) on December 12-14, 2005 to demonstrate functionality and control of the 5kW-02 system and the hydrogen purification system.

Task 3.6 Milestones

3.6.1. Stack conditioning
3.6.2. Stack start-up
3.6.3. Stand alone tests
3.6.4. Grid-Tie tests
3.6.5. Load step tests
3.6.6. Control system fault response tests

3.6.1. Stack conditioning

Each of the sixteen 25-cell stacks for the hot box assembly was conditioned on a 50-cell test stand to verify performance prior to installation into the 5kW-02 system. During conditioning, each stack was tested to verify minimum performance parameters. Tests included a polarization curve (current – voltage sweep), sensitivity to fuel utilization, and sensitivity to air utilization. All stacks installed in the 5kW-02 system exceeded minimum performance parameters.

3.6.2. Stack start-up

All stacks passed acceptance criteria during first start-up. Up to 4.6 kW was demonstrated at relatively low temperature (~800 C) and relatively high electrochemical efficiency (>0.8V/cell). Some control system tuning and modifications were implemented during the first week of testing.

3.6.3. Stand-alone tests

A series of stand-alone tests were performed prior to attempting grid-tie. Afterwards, the inverter was cycled 30 times between grid-tie and stand alone mode. On test #27 out of 30, the inverter failed to transition from grid-tie to stand-alone. Upon inspection, a loose wire was found. Critical wiring was better secured and the system satisfactorily passed the test. The 5kW-02 system had successful operation through a grid failure at Ion America on Thanksgiving Day.

3.6.4. Grid-Tie tests

The 5kW-02 system successfully passed 30 of 30 grid-tie tests with the new wiring configuration. By December 19, 2005 at 08:30 AM PST, the system supplied 2004 kWh of 208V/3P power to the grid, and recorded a peak system (AC power + hydrogen) efficiency of 54%.

3.6.5. Load step tests

After tuning control parameters, the system automatically controlled fuel, inverter, and all other parameters in response to load commands automatically. The bandwidth of the PC-based control system was ~20 times greater than its LabView predecessor. As a result, the system responded more crisply to load steps.

3.6.6. Control system fault response tests

All control system fault modes were tested, and the system responded properly in each scenario. The hardware Failure Modes and Effects Analysis (FMEA) was demonstrated during system operation. Most control system fault modes were tested during system operation with the real stacks in place. In all cases, the system responded properly.

Figure 30 shows a table summarizing the required test results. Figure 31 highlights the system operation, controls, and hydrogen purification system. Figure 32 shows the system availability as a function of time from November 19, 2005, until December 19, 2005, during which time the system accumulated 674 hours of run time with over 95% availability. Figure 33 shows a snapshot of the system hot box temperature map on December 1, 2005 while exporting 3.5 kW of 208V/3P power to the grid. Note that the average temperature is ~100 ºC lower than for the 5kW-01 system. Individual column currents are labeled and vary from 11.2-12.7 A, for a cumulative current of 47.5 A. Figure 34 compares operation of the 5kW-02 system in comparison to 5kW-01. The 5kW-02 system is operating at higher efficiency, lower temperature, and with a lower temperature spread than 5kW-01. It has generated significantly more energy and exported more power to the grid in less time than 5kW-01.

Test	Result	Comments
Stack start-up	**Pass**	• All stacks pass acceptance criteria during first start-up.
Stand alone tests	**Pass after modification**	• On test #27 out of 30 inverter failed to transition from grid-tie to stand-alone; loose wire was found and fixed. • Reconfigured wiring and conducted retest. Satisfactory results. • Successful operation through grid failure at Ion America on Thanksgiving Day.
Grid-tie tests	**Pass**	• Successful operation on 30 out of 30 tests.
Load response tests	**Pass**	• System controls fuel, inverter and all other parameters in response to load commands automatically.
Control system fault response	**Pass**	• All system control fault modes tested. Control system responded properly in each scenario.

Figure 30. Summary of required test results.

System Operation:

- Completed **707** hours of operation on Dec. 19th
- Produced **2614** kWh of DC power
- Sent **2004** kWh of AC power to the "grid"
- Achieved peak DC power of **4.6** kW (can be raised to 6.5 kW)
- Recorded peak system (AC Power + Hydrogen) efficiency of **54** %
- Operated at lower temperature than previous systems (**800** °C)
- Recorded very uniform temperature and current profiles among columns (demonstration of design improvements over 5kW-01)

Controls:

- System startup completely automated using industrialized control system
- Secured monitoring and control established

Hydrogen production:

- Repackaged the PSA-based hydrogen purification system in a compact container
- Verified automated compressor control while the repackaged purification system was fed anode exhaust from 5kW-02 system

Figure 31. Highlights of the 5kW-02 system operation thru December 19, 2005, status of controls, and repackaging of hydrogen purification system.

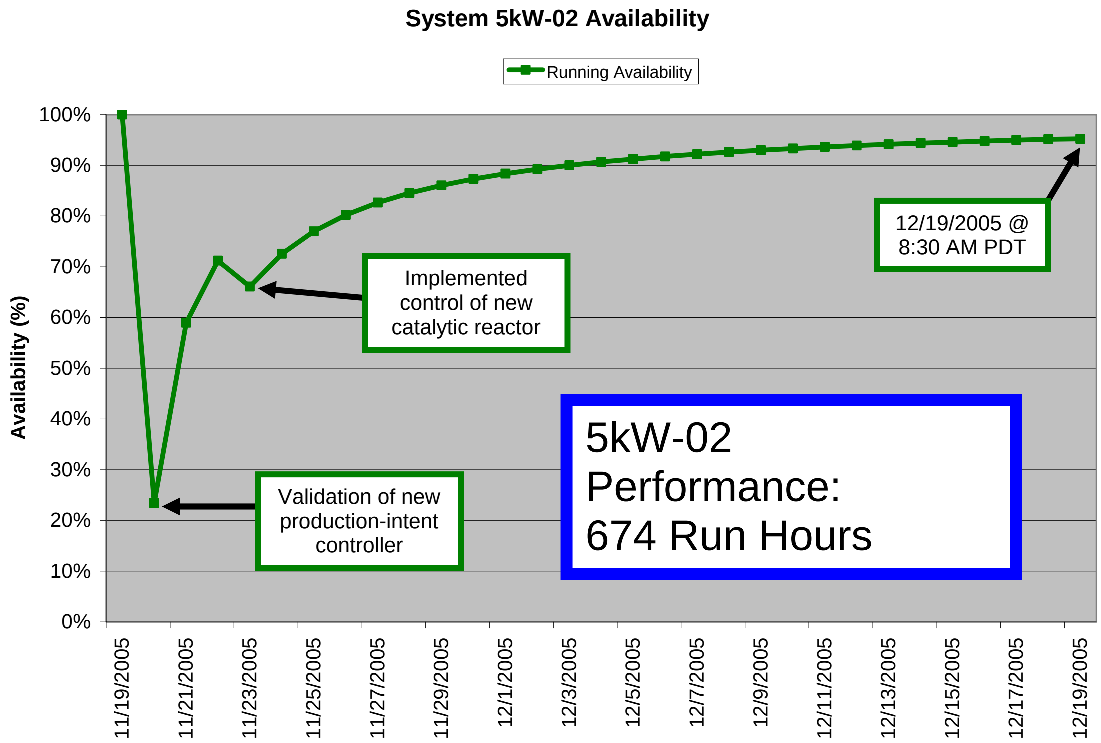


Figure 32. System availability November 19 – December 19, 2005.

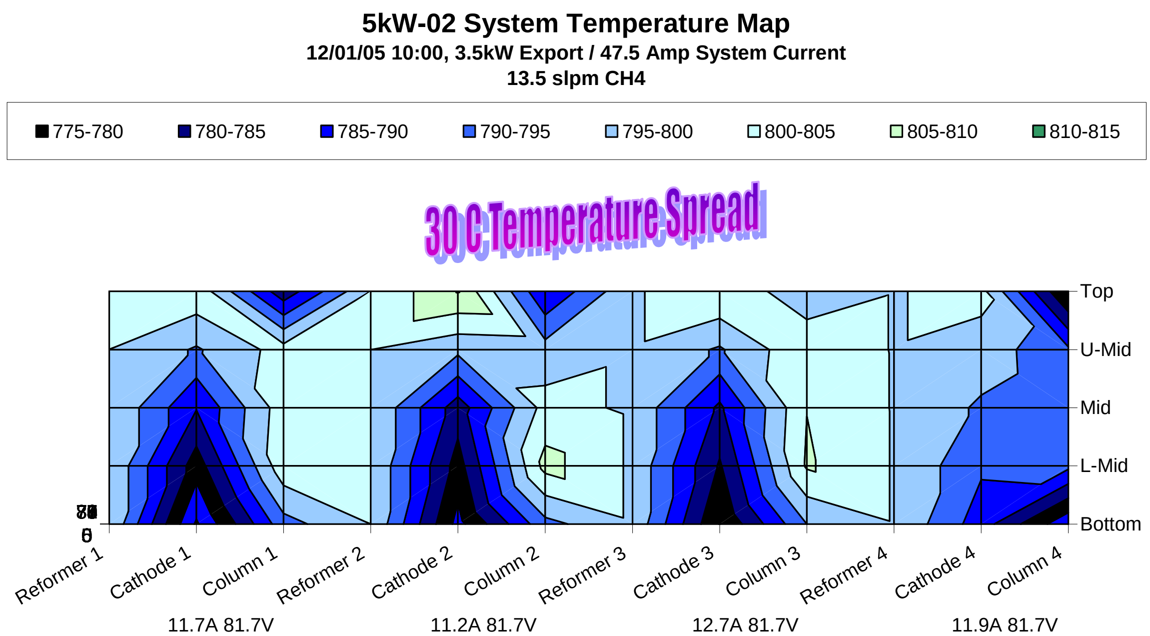


Figure 33. Hot box temperature map on December 1, 2005 while system was exporting 3.5 kW of 208/3P power to the grid.

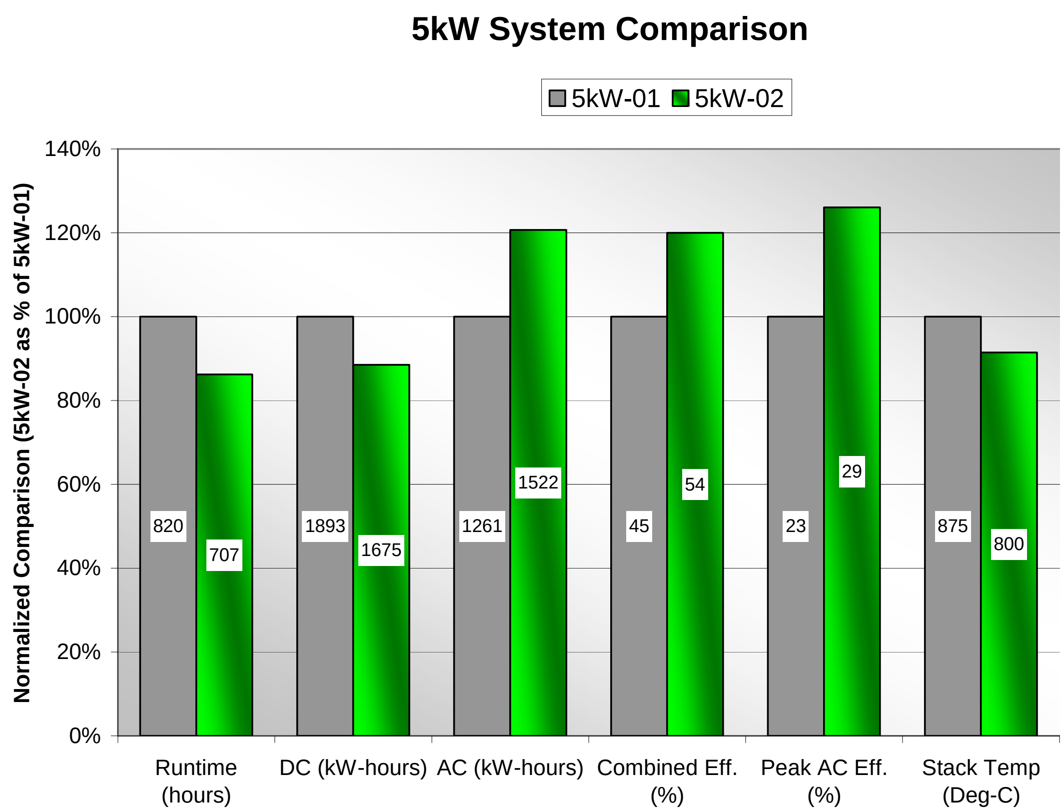


Figure 34. Comparison of 5kW-02 operation to 5kW-01 as of December 19, 2005.

3.7 System Delivery Recap

The system was packaged and shipped from Ion America facility on January 13, 2006. Crating and loading of the system went according to the plan and five crates were loaded into the US Xpress truck by 7:00 PM. Richard Centner, Oliver Grande and Suminderpal Singh arrived at UTC on January 16, 2006, to receive the system at 701 East Martin Luther King. The crates were unloaded and uncrated on January 17, 2006, and by January 19, the fuel cell and the PSA system were mounted on the concrete pads. Installation of hot box was also completed on January 19, 2006.

Ion America started making the final preparations to start the PSA and Fuel Cell during the week of January 23, 2006. The fuel cell system was initially expected to start on January 27, 2006, however because of the delay in getting the authorization for city electrical inspector's office the start-up was delayed. The fuel cell system was started on February 4, 2006, at 3:00 PM, and the system started putting out 3kW to the grid on February 5, 2006.

Task 3.7 Milestones

Milestones:

3.7.1. Ship

3.7.2. Receipt in Customer facility

3.7.3. System setup, checkout, and start-up

3.7.1. Ship

After operating the 5kW-02 system at IA for >700 hours, it was crated and shipped to UTC on January 13, 2006. Five crates were loaded into the US Xpress truck by 7:00 PM. The hot box was instrumented with shock and vibration recorders prior to crating. One shock recorder (Madge Tech) was mounted on the side of the hot box which recorded 3-axes of acceleration data. The second recorder (Lansmont) was mounted on the vertical support frame on top of the hot box and recorded four channels of accelerometer and four channels of vibration data. The data from both the units was downloaded, analyzed and the results shared in the previous report.

3.7.2. Receipt in Customer facility

Richard Centner, Oliver Grande and Suminderpal Singh arrived at UTC on January 16, night to receive the system at 701 East Martin Luther King. The day was marred with rain and wind gusts, but after quick evaluation of the unloading area it was decided to unload the system on January 17, at 9:00 AM EST. It took some time to maneuver the trailer into a desirable position from where we could start unloading the crates. At 9:42 AM EST the seal to the trailer was broken and the unloading began.

Once all the crates were unloaded and moved into the facility, we started un-crating the units. Rest of the January 17, 2006, was spent removing equipment from the crates and inspecting the system for any obvious damages.

3.7.3. System setup, checkout, and start-up (Updated)

A decision was made to extend the length of the main system pad by 16" because of the fuel cell interference with the circuit breaker mounted on the column behind the concrete pad. The pad extension was poured on January 18, and was dry enough on January 19 to place the system. The clearance between the system and the circuit breaker was adequate with the extended pad.

By January 19, the fuel cell and the PSA system (Figure 35) were mounted on the concrete pads. The hot box was lifted and mounted inside the fuel cell system (Figure 36, 37) on January 19. From January 20 to 22, most of the effort went into completing the assembly of the fuel cell system (Figure 38) and PSA unit. During the week of January 23, the resources were dedicated towards finishing the plumbing, electrical work and putting finishing touches to the fuel cell facility.

Ion America was expecting to start-up the system on January 27, 2006, but the delay in getting clearance from the City Electrical Inspector's office caused the schedule to slip by a week. The letter leveraging the sovereignty clause, thus allowing us to bypass City of Chattanooga Electrical Inspector's approval, was received from University Vice-Chancellor (Figure 39) on January 27, 2006. The 5kW-02 system was started on February 4, at 3:00 PM EST and it was generating 3kW of power by 8:00 PM on February 5. System operated at 3kW power until February 12, when the system output power was increased to 3.5kW. At 11:30 PM EST on February 16, the system output was further increased to 5kW. The system has been operational for more than 400 hours since it started generating power at UTC. Prior to shipping this unit to UTC, the system had 700 hours, and as of February 22, 2006, the system has total time clocked in excess of 1100 hours.

The computer network required to monitor system performance was installed and operational inside the fuel cell building. The networking cables inside the fuel cell lab have been terminated but we are still working with loaner switch for the UTC IT department. Currently, we are able to monitor the system from Ion America's Sunnyvale location. User Interface, which allows user to monitor the system remotely, has been installed on Prof. Jim Henry's laptop and Don Eberhart's machine. Additional computer with wireless access (Figure 40), which allows Ion America to remotely access the system in the event the university's network is down, is operational in the laboratory.

On February 17, the system was formally inaugurated by Congressman Zach Wamp (Figure 41-43). KR Sridhar, Venkat Venkataraman and Stu Aaron from Ion America were present during the official inauguration of the system.

Figure 35. After the PSA was placed in its final location and fenced-in on January 23, 2006

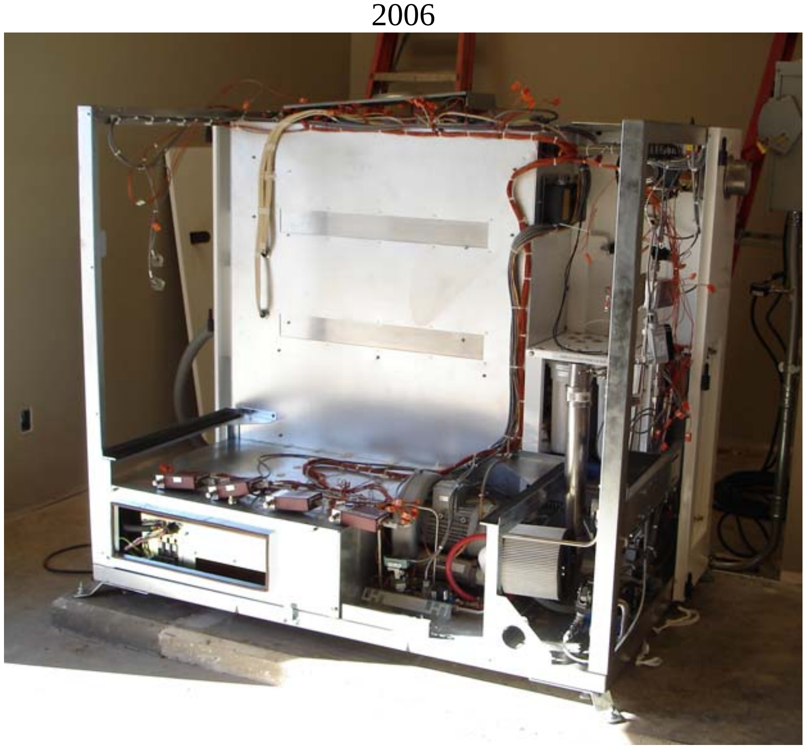
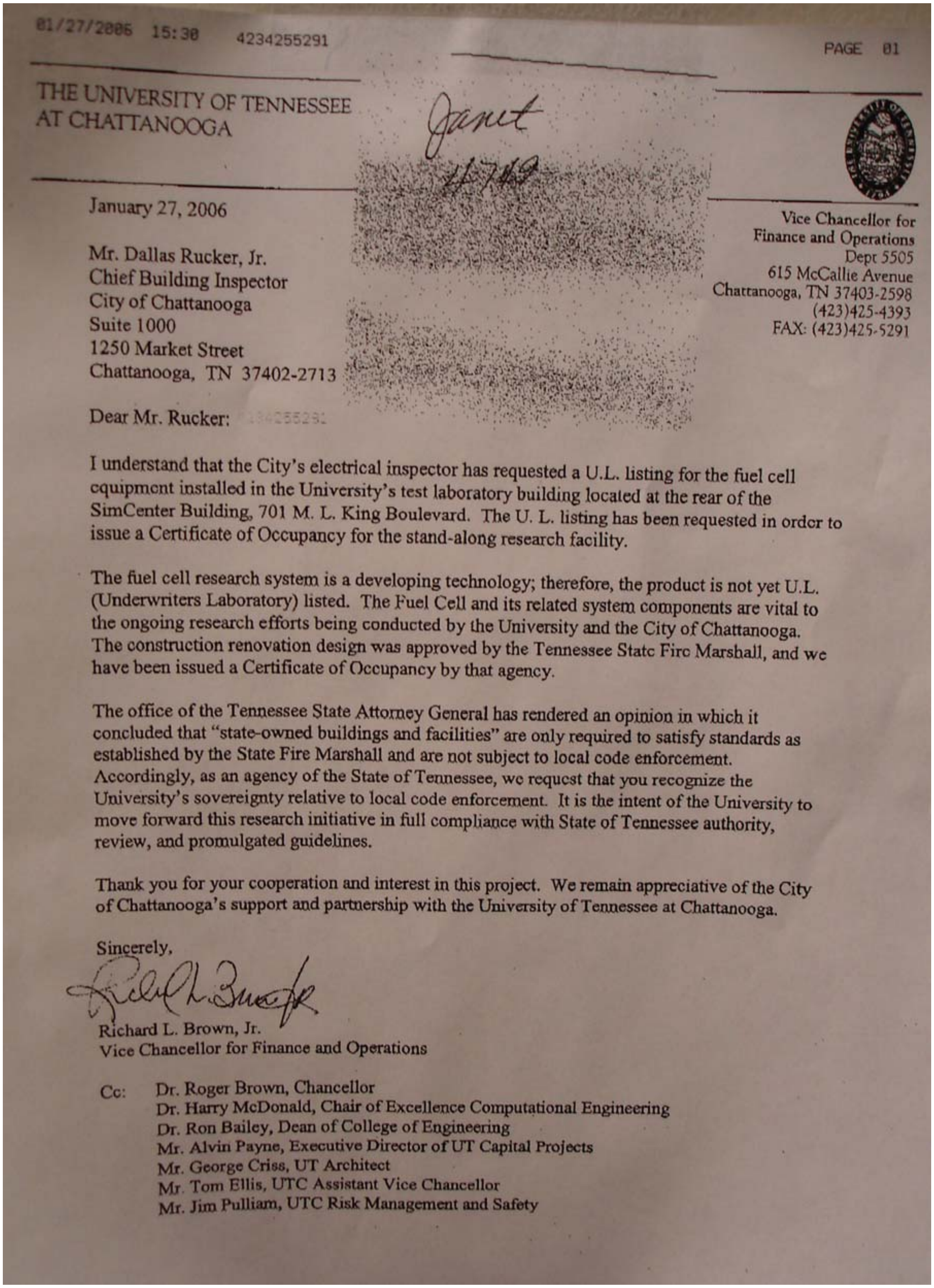


Figure 36. Fuel Cell system before installing the hot box (January 19, 2006)

Figure 37. After hot box was placed inside the fuel cell system on January 19, 2006

Figure 38. Final assembly of fuel cell system in progress on January 22, 2006



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THE UNIVERSITY OF TENNESSEE
AT CHATTANOOGA

Janet

[redacted]

Vice Chancellor for
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January 27, 2006

Mr. Dallas Rucker, Jr.
Chief Building Inspector
City of Chattanooga
Suite 1000
1250 Market Street
Chattanooga, TN 37402-2713

Dear Mr. Rucker:

I understand that the City's electrical inspector has requested a U.L. listing for the fuel cell equipment installed in the University's test laboratory building located at the rear of the SimCenter Building, 701 M. L. King Boulevard. The U. L. listing has been requested in order to issue a Certificate of Occupancy for the stand-along research facility.

The fuel cell research system is a developing technology; therefore, the product is not yet U.L. (Underwriters Laboratory) listed. The Fuel Cell and its related system components are vital to the ongoing research efforts being conducted by the University and the City of Chattanooga. The construction renovation design was approved by the Tennessee State Fire Marshall, and we have been issued a Certificate of Occupancy by that agency.

The office of the Tennessee State Attorney General has rendered an opinion in which it concluded that "state-owned buildings and facilities" are only required to satisfy standards as established by the State Fire Marshall and are not subject to local code enforcement. Accordingly, as an agency of the State of Tennessee, we request that you recognize the University's sovereignty relative to local code enforcement. It is the intent of the University to move forward this research initiative in full compliance with State of Tennessee authority, review, and promulgated guidelines.

Thank you for your cooperation and interest in this project. We remain appreciative of the City of Chattanooga's support and partnership with the University of Tennessee at Chattanooga.

Sincerely,

Richard L. Brown, Jr.
Vice Chancellor for Finance and Operations

Cc: Dr. Roger Brown, Chancellor
Dr. Harry McDonald, Chair of Excellence Computational Engineering
Dr. Ron Bailey, Dean of College of Engineering
Mr. Alvin Payne, Executive Director of UT Capital Projects
Mr. George Criss, UT Architect
Mr. Tom Ellis, UTC Assistant Vice Chancellor
Mr. Jim Pulliam, UTC Risk Management and Safety

Figure 39. Received authorization to turn on power to the fuel cell system on January 27, 2006

Figure 40. Richard Centner using wireless service to monitor the fuel cell system

Figure 41. Venkat Venkataraman standing besides the fully functional Fuel Cell system

Figure 42. Congressman Zach Wamp, standing with (from R-L) Harry McDonald, KR Sridhar and Ronald Bailey, inaugurates the fuel cell on February 17, 2006

STAFF PHOTO BY D. PATRICK HARDING

An experimental fuel cell for household power was unveiled Friday at a news conference at UTC's SimCenter. The fuel cell, run by natural gas, creates electricity and hydrogen gas.

Figure 43. Picture of the inauguration event from Chattanooga Free Press newspaper (February 18, 2006)

Conclusions and Future Directions

A 5-kW grid-parallel SOFC system for electricity and hydrogen coproduction was successfully demonstrated at IA in Sunnyvale, CA and in the newly inaugurated Alternative Energy Lab at UT-Chattanooga. Successful collaboration between The Enterprise Center, UT-Chattanooga and IA validates the synergy between governmental, academic and start-up business. A key pathway to help build a hydrogen economy without new infrastructure was successfully validated. By using equipment that coproduces electricity and hydrogen, the system operates with high capacity factor even the demand for hydrogen is relatively low.

Enhanced efficiency will be demonstrated in the future by performing technology validation projects using larger SOFC systems (100-kW class) that are already being developed at IA.

FY 2006 Publications/Presentations

1. Jim Henry and Joe Ferguson, "Chattanooga Fuel Cell Demonstration Project", U.S. Department of Energy Hydrogen Program, 2006 Annual Merit Review Meeting, Arlington, Virginia, May 16-19 (2006); http://www.hydrogen.energy.gov/pdfs/review06/tvp_5_henry.pdf

References

1. K.R. Sridhar, Jim McElroy, Fred Mitlitsky, Venkat Venkataraman, and Mark C. Williams, "Applications and Markets for Solid Oxide Regenerative Fuel Cells", 207th Meeting of The Electrochemical Society, Ninth International Symposium on Solid Oxide Fuel Cells (SOFC-IX), PV 2005-07, S.C. Singhal and J. Mizusaki, Editors, Quebec City, Canada, May 15-20 (2005).

2. Darren Hickey, Mark Cassidy, Jim McElroy, Fred Mitlitsky, and Venkat Venkataraman, "Optimization and Demonstration of a Solid Oxide Regenerative Fuel Cell System ", 207th Meeting of The Electrochemical Society, Ninth International Symposium on Solid Oxide Fuel Cells (SOFC-IX), PV 2005-07, S.C. Singhal and J. Mizusaki, Editors, Quebec City, Canada, May 15-20 (2005).

3. The Department of Energy's Fuel Cell Report to Congress, February (2003); http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb2003.pdf

Acronyms

BoM – Bill of Materials
BoP – Balance of Plant
CAD – Computer Aided Design
FMEA – Failure Modes Effects Analysis
GC – Gas Chromatograph
GGE – Gallons of Gasoline Equivalent
IA – Ion America
NG – Natural Gas
OGA – Online Gas Analyzer

PCS – Power Conditioning System
PEMFC – Polymer Electrolyte Membrane or Proton Exchange Membrane fuel cell
PSA – Pressure Swing Adsorption
SOFC – Solid Oxide Fuel Cell
SORFC – Solid Oxide Regenerative Fuel Cell
UT-Chattanooga – University of Tennessee at Chattanooga